National Aeronautics and Space Administration

Mission Concept Study

Planetary Science Decadal Survey
Mars 2018 MAX-C Caching Rover

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Data Release, Distribution, and Cost Interpretation Statements

This document is intended to support the SS2012 Planetary Science Decadal Survey.

The data contained in this document may not be modified in any way.

Cost estimates described or summarized in this document were generated as part of a preliminary concept study, are model-based, assume a JPL in-house build, and do not constitute a commitment on the part of JPL or Caltech. References to work months, work years, or FTEs generally combine multiple staff grades and experience levels.

Cost reserves for development and operations were included as prescribed by the NASA ground rules for the Planetary Science Decadal Survey. Unadjusted estimate totals and cost reserve allocations would be revised as needed in future more-detailed studies as appropriate for the specific cost-risks for a given mission concept.

Planetary Science Decadal Survey

Mission Concept Study Final Report

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Executive Summary

The proposed 2018 Mars Astrobiology Explorer-Cacher (MAX-C) caching rover would be a NASA-built mid-class rover that would be the first component in a Mars sample return campaign strategy. NASA is projecting to launch the proposed MAX-C rover with the European Space Agency's (ESA's) ExoMars mission on a U.S.-provided launch vehicle in mid 2018; the entry, descent, and landing systems would use the "Sky Crane" approach developed for Mars Science Laboratory (MSL) to land a pallet with both rovers secured onboard onto the surface of Mars. After the rovers egress from the pallet, there would be a period of checkout for both rovers. MAX-C would be designed to operate on the surface of Mars for 500 sols. The MAX-C rover suite of science instruments would be used to identify and target potential rock samples and a sample handling, encapsulation, and caching system to obtain and preserve samples for eventual return to Earth by a potential future Mars Sample Return mission.

Acquisition and return to Earth of martian materials has been a high science priority since the 1970s. The proposed MAX-C would start the sequence of missions that would enable this high-priority objective to be accomplished. The proposed scientific objectives for this mission are as follows:

- At a site interpreted to represent high habitability potential, and with high preservation potential for physical and chemical biosignatures:
  - evaluate paleoenvironmental conditions,
  - characterize the potential for the preservation of biotic or prebiotic signatures, and
  - access multiple sequences of geological units in a search for possible evidence of ancient life and/or prebiotic chemistry.
- Samples necessary to achieve the proposed scientific objectives of the potential future sample return mission should be collected, documented, and packaged in a manner suitable for potential return to Earth.

The proposed MAX-C rover would have the dual objectives of conducting high-priority in situ science and obtaining rock samples for eventual return to Earth. To ensure access to the scientifically most interesting samples, MAX-C would be designed to rove 20 km over a 500-sol nominal lifetime. It would feature mast-based remote sensing instrumentation, arm-based in situ measurement capability, and the ability to obtain rock cores for a primary and contingency pair of sample caches. These caches would be collected during a subsequent mission by a fetch rover for return to a Mars ascent vehicle for eventual return to Earth.

The key elements in this mission would include

- The MAX-C rover, with its sampling system, caches, and instrument suite
- The ExoMars rover, with its sampling system and instrument suite
- The landing pallet
- The descent stage
- The entry system
- The cruise stage

ESA would provide the ExoMars rover, its sampling system, and its instrument suite; and NASA would provide the remaining elements.

1. Scientific Objectives

Science Questions and Objectives

The Mars Astrobiology Explorer-Cacher (MAX-C) mission, a proposed rover to be launched in 2018, would have the dual objectives of conducting high-priority in situ science and obtaining rock samples for eventual return to Earth.

The current emphasis of the Mars Exploration Program is to answer the question “Did life ever arise on Mars?” Exploration for life on Mars requires a broad understanding of integrated planetary processes in order to identify those locations where habitable conditions are most likely to exist today or to have existed in the past and where conditions are or were favorable for preservation of any evidence of life. Therefore, this endeavor must also investigate the geological and geophysical evolution of Mars; the history of its volatiles and climate; the nature of the surface and subsurface environments, now and in the past; the temporal and geographic distribution of liquid water; and the availability of other resources (e.g., energy) necessary for life.

Accordingly, assessing the full astrobiological potential of martian environments requires much more than identifying locations where liquid water was present. It is also necessary to characterize more comprehensively the macroscopic and microscopic fabric of sediments and other materials, identify any organic molecules, reconstruct the history of mineral formation as an indicator of preservation potential and geochemical environments, and determine specific mineral compositions as indicators of coupled redox reactions characteristic of life. The requirement for such information guides the selection, caching, and return of relevant samples in order to address the life question effectively in sophisticated laboratories on Earth.

The acquisition and return to Earth of martian materials has been a high science priority since the 1970s. The proposed MAX-C would start the sequence of missions to enable Mars sample return to be accomplished in a way that effectively would address the search for evidence of life.

To ensure access to the scientifically most valuable samples, MAX-C would be designed to rove 20 km over a 500-sol nominal lifetime. It would feature mast-based remote sensing instrumentation, arm-based in situ measurement capability, and the ability to obtain rock cores for a primary and contingency pair of sample caches. These caches would be retrieved during a subsequent mission by a fetch rover for return to a Mars ascent vehicle for eventual return to Earth.

Prioritized Science Objectives

The proposed scientific objectives for this mission are as follows:

- At a site interpreted to represent high habitability potential, and with high preservation potential for physical and chemical biosignatures:
  - evaluate paleoenvironmental conditions,
  - characterize the potential for the preservation of biotic or prebiotic signatures, and
  - access multiple sequences of geological units in a search for possible evidence of ancient life and/or prebiotic chemistry.
- Collect, document, and package (in a manner suitable for potential return to Earth) the samples necessary to achieve the proposed scientific objectives of the potential future sample return mission.

Table 1-1 describes the linkages between the proposed science objectives and how they would be achieved. Note that functional requirements are requirements placed by science on the mission concept (e.g., requirements on the spacecraft, trajectory, mission architecture, etc.).

Driving Requirements

In addition to the scientific objectives, MAX-C would have a number of driving requirements based on programmatic and engineering considerations. These proposed requirements are as follows:

- Land on terrain with elevations relative to the Mars Orbiter Laser Altimeter (MOLA)–defined areoid of up to −1 km and within a latitude belt between 15°S and 25°N with a 3-sigma landing error ellipse of 11 km.
- Drive 20 km to access important geological materials for imaging and spectral characterization using remote sensing instrumentation, followed by contact-based elemental, mineralogical, and textural measurements of natural rock surfaces and interior surfaces exposed by brushing and grinding.
- Acquire 19 primary and 19 contingency rock cores, each 10 g in mass, for rock targets shown by MAX-C remote sensing and contact measurements to provide a high likelihood of preserving evidence for past environmental conditions, habitability, and perhaps life. Place these cores in primary and contingency caches for retrieval by a subsequent mission and fetch rover. Two caches would be needed to maximize the probability of getting samples back to Earth (e.g., if first cache is lost due to ascent vehicle failure or if the MAX-C roves to an area that could not be accessed by the fetch rover.)

Science Traceability

Table 1-1. Science Traceability Matrix

Science Objective	Measurement	Instrument	Functional Requirement
Cache system Acquire, package, and preserve a rock core sample cache for return to Earth that has a high likelihood of containing information needed to reconstruct past environmental conditions and information about habitability and life	Acquire, package, and preserve rock core	Dual cache system with two sample carousels	Acquire rock cores, encapsulate, and deliver to a caching system
			Contain 19 primary rock cores
			Deliver samples to the cache without contaminating other samples in the cache, or damaging or degrading other capabilities
			Validate that samples have been delivered to the caching system
			Each rock core mass to be 10 g
			Ability to dispose of three samples and change-out for three new samples
			Ability to release and store contingency cache
			Avoid excess heating, monitor pressure and temperature
			Survive intact on surface for at least 10 years
Ability to collect sample of near-surface rock	Collect rock sample	Coring tool on arm	Must be able to core into rocks with variable hardness and grain size distribution
			Have sufficiently low dust and vibration levels to not damage or degrade other capabilities
			Have ability to change worn-out bits
			Samples must not become mixed/contaminated

Science Objective	Measurement	Instrument	Functional Requirement
Must retain pristine nature of samples prior to arrival on Earth	Encapsulate sample	Encapsulation sleeves associated with coring tool	Avoid excess heating
			Need ability to relate specific core samples to acquisition time and location, e.g., by labelling cores
Ability to link sample to field context Identify and select samples that are different from each other by imaging (in visible light) the morphology of naturally occurring and disturbed (by MAX-C) landforms, soils, and rocks	Wide-angle stereo. High resolution.	Pancam + Vis-NIR filtering on rover mast— in a position that allows the imager to observe the maximum area around the rover	Spectral filter sets 400 nm–1 mm, at least 12 filters
			Sensitivity at least as good as Mars Exploration Rover (MER)
			Angular resolution at least as good as Pancam on MER
Capable of determining the texture of rocks and soils in situ. Ability to image the surface on the scale of 100s of microns prior to, during, and after coring operations	Texture and microscopic imaging	Microscopic Vis-IR imager in a position that allows the imager to observe the maximum area around the rover	Spectral resolution, spatial resolution, and sensitivity at least as good as MER
Spatially resolved mineralogical and organic compound detection (and mapping)	Mineralogy and organic detection	Raman point or mapping spectroscopy on the arm. Needs a rock abrasion tool (RAT) for full capabilities.	Green and deep UV Raman Beam size of <10 mm
Clean target face before analysis		RAT on arm	Similar to MER
Capable of measuring the bulk concentration of major chemical elements of surfaces *beneath* dust and thin coatings (<several millimeters) in situ using contact measurements	Bulk chemistry	RAT and Alpha Particle X-ray Spectrometer (APXS) on arm	At least as good as MER

2. High-Level Mission Concept

Overview

The proposed Mars 2018 MAX-C caching rover mission would launch NASA's MAX-C and ESA's ExoMars rovers and land them together on a pallet using the "Sky Crane" concept developed for MSL. The strawman instrument set includes a panoramic camera, a near-infrared (NIR) spectrometer, a microscopic imager, an Alpha Particle X-Ray Spectrometer (APXS), and a dual wavelength Raman spectrometer. These instruments would locate, study, and select samples for possible return to Earth. These samples would be acquired and encapsulated by MAX-C's sampling handling system and deposited in a cache or a backup cache. The caches would be placed on the surface of Mars to await retrieval by a fetch rover from the proposed future Mars Sample Return mission.

The proposed MAX-C rover 2018 mission would be launched in May 2018 on a NASA-supplied Atlas V 531–class launch vehicle on a Type I trajectory and would arrive approximately 8 months later in January 2019, at the tail end of the martian dust storm season. The rovers would land in a region of Mars between latitudes 25°N and 15°S.

The rovers would be enclosed in an aeroshell inside the cruise stage for the duration of cruise. Prior to atmospheric entry, the entry system would be released from the cruise stage. The entry system would consist of the aeroshell, which would protect the pallet and rovers during cruise and entry, and a supersonic parachute (and deployment system) to slow the entry vehicle until the Sky Crane, pallet, and rovers could be released from the aeroshell. The entry system would separate the aeroshell system from the cruise stage, deploy the parachute, release the heat shield, and then separate the descent stage from the entry system. The descent stage would employ a platform above the pallet and rovers to provide a powered descent and a Sky Crane to lower the pallet and rovers onto the surface of Mars. After the pallet has touched down, the descent stage would cut the bridle and umbilical cables to free itself from the pallet and then fly away from the rover's touchdown site.

Once the pallet has been deployed onto the martian surface, bipods could be articulated in order to level the platform and provide a more controlled egress path from the top deck. Egress would be accomplished utilizing inflated textile egress ramps deployed over the deployed bipods, thereby providing a safe and controlled path in any direction from the top deck of the landing pallet.

After egress, the two rovers would go through a checkout period and then begin science operations. The proposed MAX-C rover would be expected to collect a total of 38 samples, 19 in each of two sample caches. The mission would be required to last 500 sols (514 Earth days) and traverse at least 20 km.

Concept Maturity Level

MAX-C design requirements requested by the Planetary Science Decadal Survey Mars Panel were reviewed against the Jet Propulsion Laboratory's (JPL's) concept maturity level (CML) guidelines (Table 2-1). JPL reviewers determined that MAX-C is at CML 4. Two NASA Science Advisory groups reviewed the proposed science objectives and traceability, and a joint NASA-ESA Science Advisory Group is studying joint operations of the two rovers. NASA and ESA have defined and agreed upon their respective responsibilities. The ExoMars rover is in an advanced state of development and the instruments have been selected. The proposed MAX-C rover and the remaining flight elements are in preliminary design at the pre-Phase A level.

Table 2-1. Concept Maturity Level Definitions

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Technology Maturity

This mission concept would require the development of several capabilities prior to the mission preliminary design review (PDR). The technology challenges are described below.

Sample Acquisition and Encapsulation

NASA has limited experience in planetary sample acquisition. On Mars, the experience is limited to Viking and Phoenix scoops for sampling regolith. The proposed MAX-C rover would acquire rock cores (~20 cores, ~1 cm × ~5 cm). The core samples would have to be collected in sample tubes, sealed, and registered to the specific locations on the surface of Mars. Rock core sampling is the key challenge. Currently, no flight heritage system is available to perform this function. There is, however, a considerable technology development history in this area. In addition to many prototyping efforts in the past, two coring tools were developed by Honeybee Robotics for Mars applications (Mini-Corer and Corer-Abrader Tool, or CAT) that were flight prototypes. Current maturity for the system as a whole (i.e., coring tool, sample handling) and controls is technology readiness level (TRL) 3.

Terrain-Relative Descent Navigation and Precision Landing

Since the proposed MAX-C and ExoMars rovers would land together on a pallet rather than on rocker-bogie wheels, a capability is needed to ensure safe landing through the avoidance of rocks and slopes. This technology could be used to guide the lander to perform a lateral divert maneuver to a safe landing location, just prior to touchdown. This technology is currently TRL 3–4.

Mobility

Increasing the Average Rover Speed

The average rover speed could be increased by reducing the time that is required to compute the “sense” and “think” portion of a move cycle. Currently, each half-a-meter move cycle takes as long as 350 s for a 20-s move. The approach would be to speed up the computations using co-processors. This technology is TRL 4.

Reducing Control Electronics Volume and Mass

The volume and mass of the motor control electronics could be reduced by using a decentralized motor controller architecture. This would require the development of credit card–size controllers that would be co-located with the motors and operate in the Mars ambient temperatures. This technology is TRL 5.

Round-Trip Planetary Protection

The proposed 2018 MAX-C/ExoMars mission is expected to be categorized as Class IVa overall and Class IVb for the sampling system. See Section 3 for a discussion of the proposed 2018 MAX-C round-trip planetary protection.

Instruments

Three of the instruments (Pancam, Microscopic Imager [MI], and APXS) have previously flown on missions and are TRL 9.

The current fluorescence/Raman band instrument concept is TRL 5. The current version of the instrument has been tested in the Antarctic, the Arctic, the Mojave Desert, and Svalbard (Norway) with funding by NASA Astrobiology Science and Technology Instrument Development, NASA Astrobiology Science and Technology for Exploring Planets, U.S. Army, and U.S. Defense Threat Reduction Agency. No flight heritage exists for this instrument. The modifications currently being made are associated with miniaturization of the spectrometer and laser source.

The NIR spectrometer concept is based on a simplified version of the concept Mini-M3, a modified design of a previous instrument (Moon Mineralogy Mapper [M^3]), and, as such, claims moderate heritage. All major NIR spectrometer components have flown in space on previous missions are flight qualified. Instrument modifications are primarily packaging, thermal design, and simplification of the electronics. Mini-M3 is TRL 6.

Because these instruments would be selected under a competitive announcement, the technology development for these instruments is not included as part of the 2018 technology development program.

Key Trades

The MAX-C team has already addressed a number of key trades, some of which strongly benefited from the MSL extensive review and similar trades during its design. Many of these trades focus on the landing system. For both MSL and the proposed 2018 mission, extensive reviews of the airbag architecture (Mars Pathfinder, MER) versus the Sky Crane architecture (MSL) versus the legged lander (Viking, Phoenix) have been conducted. In addition, the capability of landing on a pallet versus landing on wheels has been newly explored for 2018. In order to accommodate the two rovers, the team also reviewed the implications of staying with an aeroshell size of 4.5 m or increasing the aeroshell to a diameter of 4.7 m. The team also studied the shape of the aeroshell, using either the Apollo aeroshell or the Viking aeroshell (which is used on MSL) and concluded that the Viking aeroshell at 4.7 m provided adequate margin for accommodating all the flight elements.

Several key trade studies remain to be conducted. These include the following:

- Landing platform and egress aids to accommodate MSL-like hazards

  A study will assess the trades between platform capabilities and hazard reduction through base-lined terrain-relative navigation rock hazard detection and avoidance, and/or landing site restrictions.

- Volume available in aeroshell

  Options for a more volumetrically efficient heat shield shape need to be explored while the team also studies the options to reduce rover size (e.g., modest mobility reductions, optimized internal layout, aspect ratio trades).

3. Technical Overview

Strawman Instrument Payload Description

The MAX-C strawman payload consists of a complementary set of five optical and spectrometry instruments that would be used to select and analyze samples to understand past environmental conditions and the probability of conditions for habitability. The most interesting samples would be stored in primary and backup sample caches that would potentially be returned at a later date by the proposed Mars Sample Return mission. The payload represents a mix of already-flown instruments (Pancam, APXS, and MI, all TRL 9) and newer proven technologies (NIR point spectrometer, Raman spectrometer, both TRL 5). A summary of payload mass and power (Table 3-11) follows the instrument discussions below.

Pancam

The Pancam (Table 3-1) is a high-resolution stereo imager that has flown previously on both MERs and the Phoenix lander. Images from Pancam would be used to identify potential sampling sites in the field and evaluate them in the context of their surroundings. Pancam would be used in studies of morphology, topography, and geology, as well as in studies of atmospheric dust and opacity. Pancam consists of two digital cameras, each with a 1024 × 1024 active imaging area from transfer charge-coupled device (CCD) detector array. Each camera includes a small eight-position filter wheel to allow multispectral studies in the 400–1100 nm wavelength range. The optics has an effective focal length of 43 mm and a focal ratio of f/20, for an instantaneous field of view (FOV) of 0.27 mrad/pixel and a FOV of 16° × 16°. Pancam would be used to generate panoramas of the landing site area and other important sites. Imaging of the martian sky would be done on a periodic basis, together with imaging of the sun through the solar filters to determine aerosol properties. Calibration would be performed through a variety of means: a brief calibration campaign at the beginning of the mission, imaging of the sky and sun, downlinking reference pixel and dark current images, and imaging of the calibration target.

Table 3-1.Pancam (Mast)

Item	Value	Units
Panorama camera 2×		
Number of channels	2	
Size/dimensions	50 × 60 × 110	cm × cm × cm
Instrument mass **without** contingency (CBE*)/ per unit	1.2	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	1.6	kg
Instrument average payload power **without** contingency (80% during mast science) / per unit	2.4	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	3.1	W
Instrument average science data rate^ **without** contingency	8000	kbps
Instrument FOVs (if applicable)	16.8 × 16.8	degrees
Pointing requirements (knowledge)	0.1	degrees
Pointing requirements (control)	2	degrees

**CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

NIR Spectrometer

The NIR spectrometer (Table 3-2) is a passive instrument that operates in the visible and short-wave infrared (SWIR) portion of the spectrum to provide detailed mineral maps of the surrounding terrain and the mineral composition of specific rocks and outcrops. Spatial resolution varies with distance from the target, reaching down to a few millimeters at distances below 10 m. Its spectral range and spectral resolution are similar to those of the orbiting Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) and Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA) instruments, allowing extension of the orbital measurements to higher spatial resolution in addition to providing "ground truth" data. The NIR spectrometer has no mechanisms other than the scanning in x and y provided by the mast. Each pixel is simultaneously imaged in ~420 spectral bands over a range of 400–2200 nm where the spectral resolution is 5 nm.

Table 3-2. NIR Point Spectrometer (Mast)

Item	Value	Units
Number of channels	1	
Size/dimensions	2000 × 90 × 200	mm × mm ×mm
Instrument mass **without** contingency (CBE*)/ per unit	3.5	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	4.6	kg
Instrument average payload power **without** contingency (80% during mast science)	9.6	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	12.5	W
Instrument average science data rate^ **without** contingency	8000	kbps
Pointing requirements (knowledge)	0.1	degrees

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Microscopic Imager

The MI (Table 3-3) is a high-resolution imager that would be mounted on the turret on the proposed MAX-C arm. MI has previously flown on MER. The MI would be used to image the fine-scale morphology, texture, and reflectance of surfaces and to identify areas for further study by other turret instruments as well as areas for sampling. The MI uses a camera body identical to that of Pancam and has the same radiometric performance as Pancam. The MI has a focal length of 20 mm and a working distance of 63 mm from the front of the lens barrel to the object plane. MI's spectral range is 400–680 nm. The MI has a transparent dust cover that remains closed except during operations, and the instrument uses a contact sensor to ensure correct positioning and prevent accidental damage. MI would be used in conjunction with the Raman and APXS to select the desired area for sampling; therefore, the MI must be able to accurately image the same areas as the Raman.

Table 3-3. Microscopic Imager (Arm) MI Design

Item	Value	Units
Number of channels	1	
Size/dimensions	80 × 80 × 100	mm × mm × mm
Instrument mass **without** contingency (CBE*)/ per unit	0.3	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	0.4	kg
Instrument average payload power **without** contingency (3% during arm science)	0.3	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	0.4	W
Instrument average science data rate^ **without** contingency	8000	kbps
Instrument FOVs (if applicable)	31 × 31	mm

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Alpha-Particle X-Ray Spectrometer (APXS)

The Alpha-Particle X-Ray Spectrometer (APXS, Table 3-4) is a contact instrument that uses X-ray spectroscopy to determine the elemental composition of soils and rocks with a focus on iron-bearing minerals. Radioactive sources contained within the APXS sensor head irradiate the sample material, resulting in X-ray emissions that are characteristic signatures of the chemical elements within the material. An energy dispersive X-ray detector provides x-ray spectra from 700 eV to ~25 keV with energy resolution of ~150 eV at Fe K_{α}, covering elements from atomic number Z=11 to 35 and beyond. Measurement spot size in contact is approximately 1.5 cm. Operation of the APXS would require the preparation of the surface to be observed by a RAT-like tool in the sampling system and placement of the APXS on the target for a specific length of time dependent on the target. The APXS on MAX-C would be identical to the unit being flown on MSL, and derives heritage from the APXS on MER. APXS consists of a sensor head on the turret, electronics in the rover chassis, and a calibration target mounted on the rover chassis.

Table 3-4. APXS (Arm)

Item	Value	Units
Number of channels	1	
Size/dimensions	105 × 60 × 90	mm × mm × mm
Instrument mass **without** contingency (CBE*)/ per unit	1.7	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	2.2	kg
Instrument average payload power **without** contingency (42% during arm science)	5.6	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	7.3	W
Instrument average science data rate^ **without** contingency	18	kbps
Instrument FOVs (if applicable)	15	mm

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Dual Wavelength Raman/Fluorescence Instrument

The Raman/fluorescence instrument (Table 3-5) is an arm-mounted system for detection and characterization of organics in martian rocks. As a first-order capability, the dual-wavelength Raman/fluorescence instrument would enable micro-mineralogy coupled to sub-parts-per-billion in situ detection of organics to identify samples for high-priority caching interest. However, to avoid possible loss of detected organics during caching or as a result of caching, the instrument would enable the equally important in situ mapping and characterization of organics with spatially correlated mineralogical context and could lead to a clear understanding of whether the organics are a result of endogenous or exogenous processes (planetary processes or meteoritic/astroidal/cometary impacts). In addition to organics and mineral analysis, the dual-wavelength Raman/fluorescence instrument would detect and map variations in water content with detection limits down to monolayers. By coupling to imaging data from the NIR spectrometer and MI investigations of minerals and textures, a comprehensive characterization of minerals at a variety of spatial scales becomes possible, providing a clear perspective on the formation and subsequent alteration of these minerals. These investigations avoid sample handling and would require minimally processed surfaces (abrading) in a manner that preserves the spatial information.

The dual-wavelength Raman/fluorescence instrument is an active device that utilizes a deep ultraviolet (UV) laser source at 248 nm to simultaneously obtain Raman and native fluorescence signals from organics on the sample and a visible 532 nm laser for characterization of minerals by Raman spectroscopy. The complete instrument consists of an arm-based detection head with electronics located in the rover body. The instrument operates from distance of ~50 mm and has a 1 mm depth of focus. Hyperspectral spatial maps for both the organics and minerals are acquired over 1 cm^2 by rastering a <50 µm laser spot. Upon illumination with each laser, the collected light is directly injected to a fiber-less, short–focal length, dual-wavelength UV-Vis spectrometer that disperses the light over a single spectrographic CCD. For the organics separation of the Raman and fluorescence regions is made possible by excitation in the deep UV and allows for the combined advantage of low limits of detection with native fluorescence, and characterization with the Raman. The visible and the deep UV Raman portions provide detection and comprehensive characterization of minerals and monolayers sensitivity to water. The spectral resolution is ~0.1nm (deep UV: 15 cm^{-1}/ Visible: 8 cm^{-1}).

Table 3-5. Raman Spectrometer (Arm/Body)

Item	Value	Units
Number of channels	1	
Size/dimensions	80 × 60 × 200	mm × mm × mm
Instrument mass **without** contingency (CBE*)/ per unit	5.0	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	6.5	kg
Instrument average payload power **without** contingency (42% during arm science)	10.5	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	13.7	W
Instrument average science data rate^ **without** contingency	100	kbps
Instrument FOVs (if applicable)	1	cm^2

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Sampling System

The Sampling System (Tables 3-6 through 3-11) would consist of a five degree-of-freedom manipulator arm to deploy and align the instruments and the rotary percussive coring tool (drill) as well as to provide alignment, feed, and preload for the tool. The tool would provide coring, core break-off, core retention and bit capture and release for bit change-out. The caching subsystem concept is referred to as the Sample Handling, Encapsulation, and Containerization (SHEC) subsystem (Figure 3-1). Bit change-out and sample caching are combined in the design. There is one opening in the SHEC subsystem, the port for transferring a coring bit. There are four actuators, one for combined bit carousel and sample carousel rotation, one for transfer arm rotation, one for transfer arm linear motion, and a solenoid to activate the transfer arm gripper. Multiple bits would be available for coring of various rock types, and a RAT-like function would be included in the form of an abrader bit. Sample tubes would be inserted into the bits prior to sample collection, and the sample-filled tubes would be removed from the bits post acquisition and stored in the sample canister. The sample canister would then be removed from the SHEC by the manipulator arm and left for retrieval by the proposed future Mars Sample Return mission.

Table 3-6. Cache Sample Handling, and Container

Item	Value	Units
Number of channels	1	
Size/dimensions	400 × 340 × 340	mm × mm × mm
Instrument mass **without** contingency (CBE*)/ per unit	9.0	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	11.7	kg
Instrument average payload power **without** contingency (64% during sample tool manipulation)	6.4	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	8.3	W
Instrument average science data rate^ **without** contingency	1	kbps

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-7. Corer/Abrader

Item	Value	Units
Number of channels	1	
Size/dimensions	150 × 150 × 314	Mm × mm × mm
Instrument mass **without** contingency (CBE*)/ per unit	5.0	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	6.5	kg
Instrument average payload power **without** contingency (100% during coring)	75	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	97.5	W
Instrument average science data rate^ **without** contingency	1	kbps

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-8. Mast

Item	Value	Units
Number of channels	1	
Size/dimensions	0.7 m length × 100 mm diameter	m × m
Instrument mass **without** contingency (CBE*)/ per unit	7.7	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	10.0	kg
Instrument average payload power **without** contingency (10% during Mast science)	0.8	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	1.0	W
Instrument average science data rate^ **without** contingency	0	kbps

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-9. Arm (Short, Low Pre-Load)

Item	Value	Units
Number of channels	1	
Size/dimensions	0.8	m
Instrument mass **without** contingency (CBE*)/ per unit	10.3	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	13.4	kg
Instrument average payload power **without** contingency (36% during sample tool manipulation)	7.2	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	9.4	W
Instrument average science data rate^ **without** contingency	1	kbps

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-10. Organic Blank

Item	Value	Units
Number of channels	1	
Instrument mass **without** contingency (CBE*)/ per unit	1.5	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	2.0	kg
Instrument average payload power **without** contingency (100% during coring)	2	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	2.6	W
Instrument average science data rate^ **without** contingency	0	kbps

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-11. Proposed Payload Mass and Power

Payload Element	Mass			Op. Power			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)	CBE (W)	% Cont.	MEV (W)
Pancam (mast, Phoenix, MER)	1.2	30%	1.6	3	30%	4	1.0	30%	1.3
NIR point spectrometer (mast)	3.5	30%	4.6	12	30%	16	4.0	30%	5.2
Raman spectrometer (body)	5	30%	6.5	25	30%	33	8.3	30%	10.8
APXS (mast, MSL)	1.7	30%	2.2	10	30%	13	3.3	30%	4.3
MI (arm) MI design	0.3	30%	0.4	10	30%	13	3.3	30%	4.3
Mast	7.7	30%	10.0	8	30%	10	2.7	30%	3.5
Cache sample handling and container	9	30%	11.7	10	30%	13	3.3	30%	4.3
Arm => short, low pre-load	10.3	30%	13.4	20	30%	26	6.7	30%	8.7
Organic blank	1.5	30%	2.0	2	30%	3	0.7	30%	0.9
Corer/abrader	5	30%	6.5	75	30%	98	25.0	30%	32.5
Total proposed payload mass	**45.2**	**–**	**58.9**	**175**	**–**	**229**	**58.3**	**–**	**75.8**

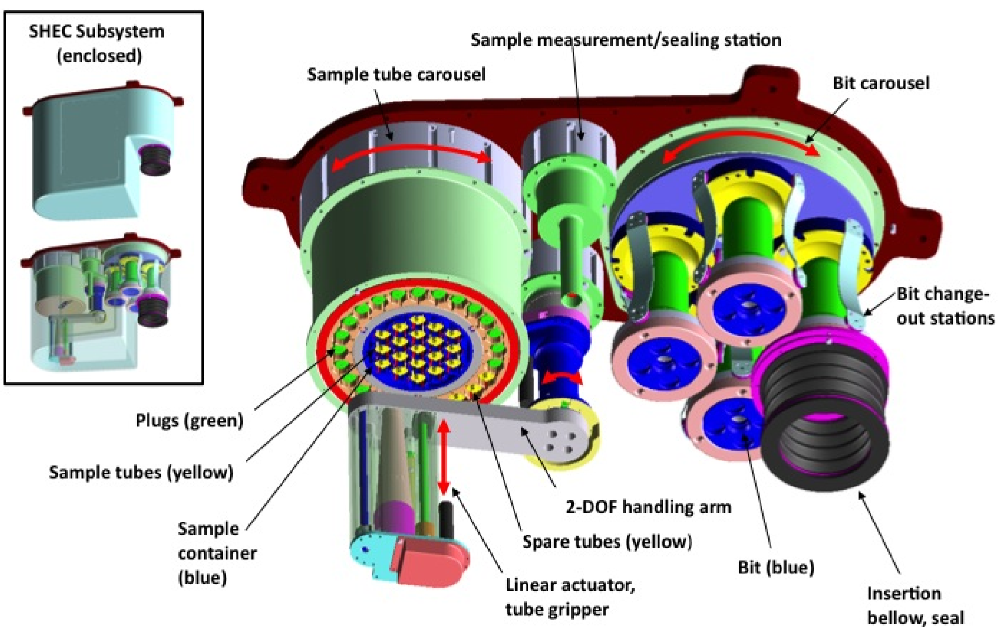


Figure 3-1. The Proposed MAX-C SHEC Subsystem.

Single cache is shown; baseline approach is dual-cache system.

Flight System

The flight system for the proposed 2018 MAX-C mission would include 6 flight elements: the MAX-C rover, the ExoMars rover, the landing pallet, the descent stage, the entry system, and the cruise stage. The MAX-C rover is a new design. The ExoMars rover is the ESA rover under development previously for the 2016 ExoMars mission. The landing pallet would carry the two rovers. The descent stage, the entry system, and the cruise stage designs are derived from the MSL entry system. The current design of each element is described in more detail below.

MAX-C Rover

The proposed MAX-C rover (Figure 3-2 and Tables 3-12 and 3-13) is envisioned as a MER-class rover, upsized to accommodate the need to collect and cache samples. The rover would be solar powered, the mobility system would accommodate 35 cm hazards, and there would be mast- and arm-mounted instrumentation. Upgrades include the ability to collect and cache samples for potential later return to Earth.

The proposed MAX-C rover would be powered by two Ultraflex solar arrays. MAX-C would be approximately 50% larger than size of the MER rover and travels on a wheelbase of approximately 1.7 m by 1.6 m providing a ground clearance of approximately 0.35 m. The rover chassis design is 1.1 m in length, 0.75 m wide, and 0.46 m tall and would support a forward mounted robotic arm supporting a dual Raman spectrometer head, an APXS head, and an MI head. A dual-canister SHEC would also be installed on the forward panel. Attached to the top deck of the chassis, an instrument mast would be used to mount a Pancam and NIR spot/line spectrometer head.

The total mass of the flight elements would be approximately 3848 kg, of which 365 kg is the MAX-C rover (including 43% margin). The total launch wet mass is estimated to be 4450 kg, which would fit on an Atlas V 531 class launch vehicle using a 2018 Type I trajectory The rover would be delivered to the surface of Mars aboard the pallet, which would be lowered by the entry and descent stages. The rover would have a single inertial measurement unit (IMU) that would be used for 3-axis attitude measurement during deployment. Forty-two distributed drive controllers and actuators would be used to perform various functions of the rover including speed and high-gain antenna (HGA) gimbal control. Four hazard cameras and two navigation cameras are provided but generally only two would be used at a time to save power.

The avionics would use the standard JPL internal approach: RAD750, critical relay control card, non-volatile memory and camera card, telecom interface card, serial interface assembly, remote engineering units, and power converters. The data storage of 4Gbits (on the NVMCAM) should be able to support the science mission with ample margin. A maximum data collection rate of 3.04 kbps (or 270 Mbits/sol) was assumed. The proposed MAX-C rover would contain new avionics development for the distributed motor controller system. The rover would employ selected redundancy on key components to address fault tolerance.

The rover would have two Ultraflex solar arrays at a total area of 6.03 m^2. The battery would use small cell Li-Ion technology in a single 30 A-Hr module. The mission would require approximately 1600 W-hrs/sol during surface operations. The MAX-C rover would utilize MSAP architecture for the electronics, which has MSL heritage.

The proposed MAX-C rover thermal design would benefit from extensive heritage from Pathfinder, MER and MSL. The rover must be able to withstand temperatures from -40°C to +50°C. The warm electronics box (WEB) and the instrument complement would be smaller than on MSL. The WEB and the battery assembly would employ MSL-heritage CO_2 insulation. Radioisotope heater units (RHUs) would be employed as they were in MER, with additional electrical heaters for warm-up and remote locations.

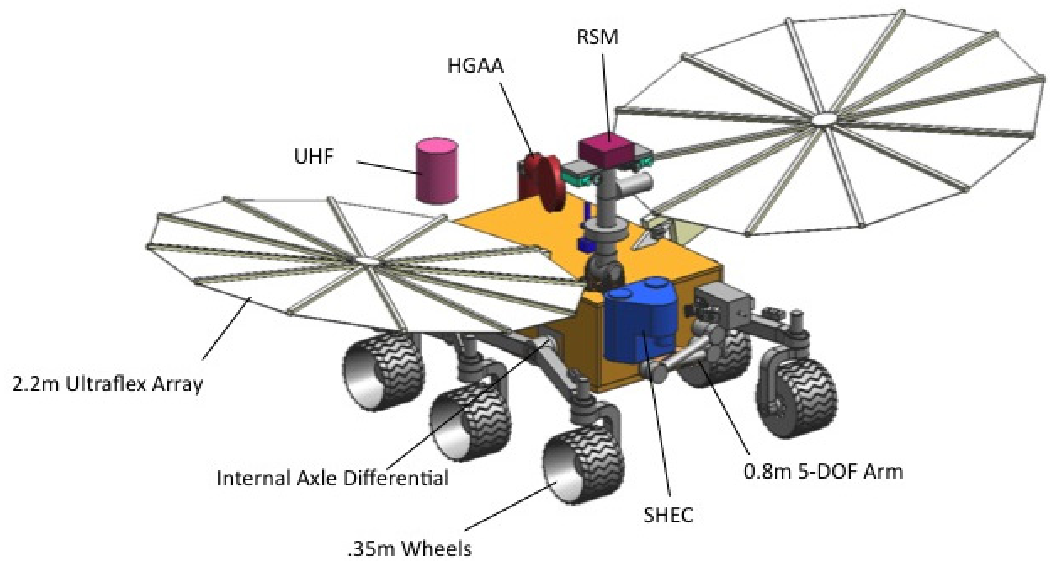


Figure 3-2. The Proposed MAX-C Rover

MAX-C would support a two-way link with Earth through all phases of the mission, consisting of direct-to-Earth (DTE) communications via X-band and at ultra-high frequency (UHF) via a relay orbiter. The telecommunications system has high heritage from MSL except that the UHF subsystem would be single string. The system would employ one 2-axis gimbaled 0.28m HGA for primary communications and one X-band low-gain antenna (LGA) as required. The system would use one small deep space transponder (SDST) for X-band communications and one UHF Electra Lite. It is expected that the relay assets would provide two passes of at least 5 minutes each sol. The use of Ka band for telecommunications from the surface of Mars is not currently feasible.

A top-level mass and power summary for the proposed MAX-C rover is shown in Table 3-12. The mass contingency policy is based on the subsystem- and system-level contingency factors. Each subsystem designer provides a contingency factor based on the degree of subsystem heritage and complexity. Once the dry mass is summed up, the total subsystem contingency is computed. A systems contingency factor is additionally applied to ensure that the total contingency is 43% (i.e., total subsystem contingency + system contingency = 43%). The 43% system contingency factor is based on the JPL design principles. The power contingency policy is to add 43% contingency to the total power for each power mode.

Table 3-12. MAX-C Mass/Power Preliminary Estimates

	Mass			Average Power		
Flight Element	**CBE (kg)**	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	94.5	30%	122.8	0	43%	0
Thermal control	16.9	19%	20.2	3	43%	4
Propulsion (dry mass)	0	0%	0	0	43%	0
Attitude control	7.5	22%	9.1	10	43%	14
Command and data handling	12.5	7%	13.4	53	43%	76
Telecommunications	15.1	7%	16.2	13	43%	19
Power	41.9	30%	54.5	27	43%	39
Total flight element dry bus mass	**254.9**	**43%**	**365**			

Table 3-13. Proposed MAX-C Rover Characteristics

Flight System Element Parameters (as appropriate)	Value/Summary, units
General	
Design life, months	500 sol
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum/titanium/composites
Number of articulated structures	1 (2-axis gimbaled HGA)
Number of deployed structures	2 (Ultraflex arrays and mast)
Aeroshell diameter, m	N/A
Thermal Control	
Type of thermal control used	Active (e.g., electric heaters, temperature sensors) and passive elements (e.g., proposed RHUs, MLI)
Propulsion	
Estimated delta-V budget, m/s	N/A
Propulsion type(s) and associated propellant(s)/oxidizer(s)	N/A
Number of thrusters and tanks	N/A
Specific impulse of each propulsion mode, seconds	N/A
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial
Attitude control capability, degrees	< 2 degrees
Attitude knowledge limit, degrees	1 degree
Agility requirements (maneuvers, scanning, etc.)	Able to traverse 20 km
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	1 articulation / 2 axes (HGA)
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	N/A
Command & Data Handling	
Flight element housekeeping data rate, kbps	2 kbits/s
Data storage capacity, Mbits	4000 Mbits
Maximum storage record rate, kbps	270 Mbits/sol (3 kbps)
Maximum storage playback rate, kbps	2 Mbps (UHF)
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Deployed Ultraflex
Array size, meters × meters	6.03
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	GaAs triple-junction Ultraflex
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	BOL = 677 W, EOL = 612 W
On-orbit average power consumption, watts	~70 W (peak = 270 W)
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	30 A-hrs

ExoMars Rover

The ExoMars rover was carried as a mass allocation of 300 kg in this study. The pallet was designed to accommodate the dimensions of both rovers, based on the current understanding of their designs.

Pallet

In an evolution of the Sky Crane delivery system, the capability of delivering a payload has been increased from delivering an individual rover to providing a flexible platform capable of supporting multiple payloads. A landing pallet (Tables 3-14 and 3-15) would interface with the descent stage at its outer edges utilizing four bipods. By moving the interface points to the outer edges, the internal area provided by the pallet would enable a variety of payloads to be delivered at any given time. In the current configuration, adequate volume is provided for both the MAX-C rover as well as ExoMars. The pallet itself would comprise a structural deck with a crushable material attached to its underside, providing rock strike protection. As described above, once the pallet has been deployed onto the martian surface, the bipods could be articulated in order to level the platform and provide a more controlled egress path from the top deck. Egress would be accomplished utilizing inflated textile egress ramps deployed over the deployed bipods, providing a safe and controlled path in any direction from the top deck of the landing pallet. The landing platform would have commanded heater elements for the stand up actuator, and temperature sensors for platform electronics and the actuator.

Table 3-14. Pallet Mass and Power Preliminary Estimates

Flight Element	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures and mechanisms	209.3	30%	272.1	0	43%	0
Cabling	11.3	30%	14.7	0	43%	0
Thermal control	0.7	6%	0.8	0	43%	0
Propulsion (dry mass)	0	0%	0	0	43%	0
Attitude control	0.6	10%	0.7	4	43%	6
Command and data handling	0	0%	0	0	43%	0
Telecommunications	0	0%	0	0	43%	0
Power	7.0	30%	9.1	4	43%	6
Total fight element dry bus mass	**229**	**30%**	**297.4**	**–**	**–**	**–**

Table 3-15. Proposed Pallet Characteristics

Flight System Element Parameters (as applicable)	Value/Summary, units
General	
Design life, months	~ Minutes (duration of EDL)
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum/titanium/composites
Number of articulated structures	1 (bipods)
Number of deployed structures	1 (egress ramp)
Aeroshell diameter, m	N/A
Thermal Control	
Type of thermal control used	Active (e.g., electric heaters, temperature sensors) and passive elements (e.g., proposed RHU, MLI)
Propulsion	N/A
Attitude Control	

Flight System Element Parameters (as applicable)	Value/Summary, units
Control method (3-axis, spinner, grav-gradient, etc.).	N/A
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial
Attitude control capability, degrees	N/A
Attitude knowledge limit, degrees	N/A
Agility requirements (maneuvers, scanning, etc.)	ACS electronics able to level pallet and lift the rover
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	0
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	ACS electronics assume that commands for leveling the pallet and lifting the rover are sent from Earth
Command & Data Handling	N/A
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	N/A
Array size, meters × meters	N/A
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	N/A
Expected power generation at BOL and EOL, watts	BOL = 677 W, EOL = 612 W
On-orbit average power consumption, watts	~ 10W (peak = 13W)
Battery type (NiCd, NiH, Li-ion)	Li-ion (Uses rover’s batteries)
Battery storage capacity, amp-hours	30 A-hrs (Uses rover’s batteries)

Descent Stage

The descent stage design (Tables 3-16 and 3-17) is based on the Sky Crane design used by MSL. The descent stage would employ a platform above the pallet and rovers to provide a powered descent and a Sky Crane to lower the pallet and rovers onto the surface of Mars. After the pallet has touched down, the descent stage would cut the bridle and umbilicals to free itself from the pallet and fly away. On the proposed 2018 mission, the mechanical/structural subsystems have been reconfigured to accommodate the landing pallet and the two payloads onboard, but the remaining subsystems derive substantial heritage from the original MSL design. Moving the interfaces to the outer edges of the descent stage makes additional surface area available on the landing pallet, thereby allowing variation in the landed payload as well as the simplified application to future missions.

The descent stage would handle all maneuvering and delta-V from cruise stage separation through landing and flyaway. It would provide one additional propellant tank (for a total of four) and larger high-pressure pressurant tanks. The system retains the heritage of the throttled MSL lander engines (MR-80B), the pulse-mode reaction control system thrusters (MR-107U), and a space shuttle–spare mechanical pressure regulator for pressure control. The propellant tanks would be ultralight composite overwrapped with titanium liners.

The entry vehicle design is 3-axis controlled during entry, descent, and landing (EDL, Figure 3-3). Gyros within the IMU would be used to propagate 3-axis attitude before and during aero-maneuvering. The IMU and MSL-type descent sensor (for altitude) would be used to trigger parachuting and Sky Crane descent. Descent motor electronics would trigger separation between the descent stage and rover. A “Multi-X” hazard reduction system would be utilized for hazard avoidance. Once the drop package is landed, leveling of the pallet and lifting of the rover would be conducted with an operator-in-the-loop.

Power systems on the descent stage derive their heritage from MSL. The descent stage uses three 9 A-hr thermal batteries. Electronics are derived from the MSL descent stage. To support

telecommunications, the descent stage has one SDST, one 100 W X-band traveling wave tube amplifier, one X-band LGA, an X-band diplexer, and a UHF patch antenna.

Table 3-16. Descent Stage Mass and Power Preliminary Estimates

	Mass			Average Power		
Flight Element	**CBE (kg)**	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	272.6	30%	354.3	0	43%	0
Cabling	37.4	30%	48.6	0	43%	0
Thermal control	23.2	26%	29.2	40	43%	56
Propulsion (dry mass)	230.8	13%	261.5	123 (burn)	43%	176
Attitude control	49.4	3%	50.8	381 (descent)	43%	544.83
Command and data handling	1.5	11%	1.7	8	43%	11
Telecommunications	12.9	4%	13.4	0	43%	0
Power	36.4	5%	38.2	24	43%	34
Total flight element dry bus mass	**668.2**	**20%**	**802.9**	–	–	–

Table 3-17. Descent Stage Characteristics

Flight System Element Parameters (as appropriate)	Value/Summary, units
General	
Design life, months	~ Minutes (duration of EDL)
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum/titanium/composites
Number of articulated structures	0
Number of deployed structures	1 (pallet)
Aeroshell diameter, m	N/A
Thermal Control	
Type of thermal control used	Active (e.g., heaters and temperature sensors) and passive (e.g., MLI) elements
Propulsion	
Estimated delta-V budget, m/s	389
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Ultra pure Hydrazine Propellant/ Helium Pressurant
Number of thrusters and tanks	8 thrusters, 4 fuel tanks, 2 pressurant tanks
Specific impulse of each propulsion mode, seconds	MLE terminal braking: 217 s RC/bank angle control: 229 s
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial
Attitude control capability, degrees	Not specified by customer
Attitude knowledge limit, degrees	Not specified by customer
Agility requirements (maneuvers, scanning, etc.)	Precision landing ellipse and hazard avoidance

Flight System Element Parameters (as appropriate)	Value/Summary, units
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	0
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	Image-correlation based "Multi-X" hazard reduction
Command & Data Handling	
Flight element housekeeping data rate, kbps	2 kbits/s
Data storage capacity, Mbits	Uses rover's CDS
Maximum storage record rate, kbps	Uses rover's CDS
Maximum storage playback rate, kbps	Not specified in CDS report
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	N/A
Array size, meters × meters	N/A
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	N/A
Expected power generation at BOL and EOL, watts	BOL = 756 W, EOL = 0 W
On-orbit average power consumption, watts	~ 350 W (peak = 712 W)
Battery type (NiCd, NiH, Li-ion)	Thermal battery
Battery storage capacity, amp-hours	9 A-hrs

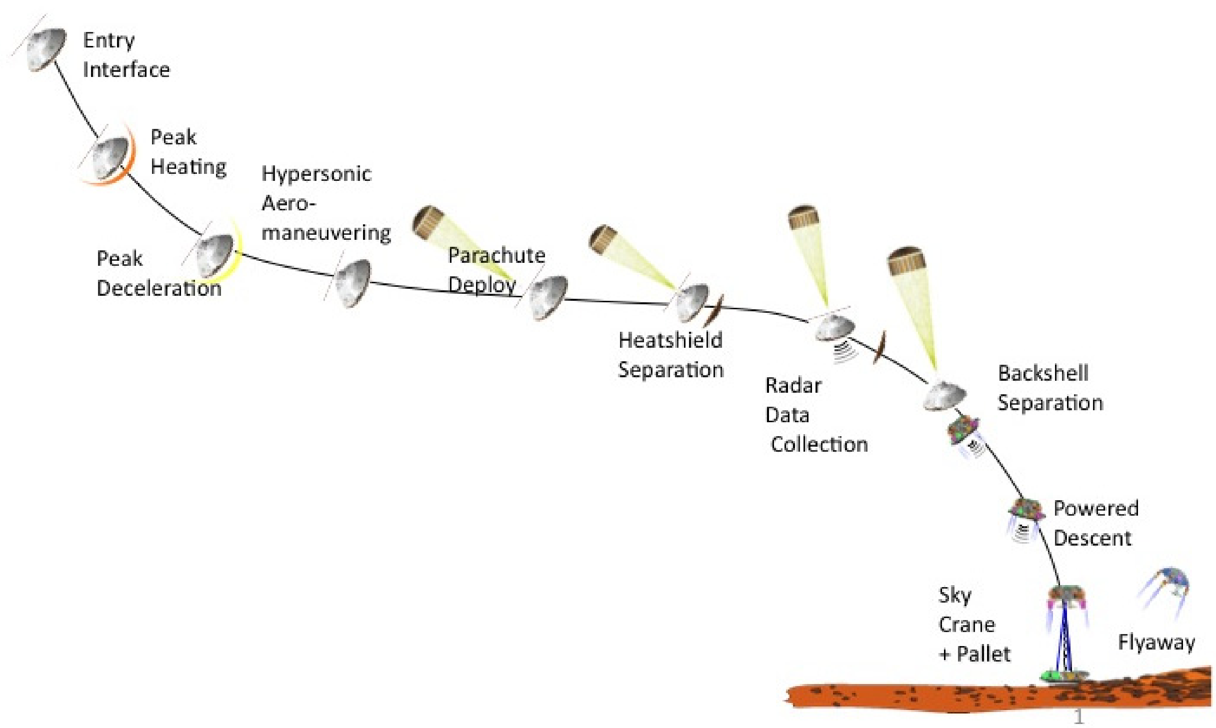


Figure 3-3. Entry, Descent, and Landing

Entry System

The entry system (Tables 3-18 and 3-19) design consists of the aeroshell that would protect the pallet and rovers during cruise and entry and a supersonic parachute (and deployment system) to slow the entry vehicle until the Sky Crane, pallet, and rovers could be released from the aeroshell. The entry system would separate the aeroshell system from the cruise stage, deploy the parachute, to release the heat shield, and then separate the descent stage from the entry system.

The 2018 mission heat shield and backshell would have a diameter of 4.7 m to accommodate the pallet and both payloads. Additionally, the heat shield would use the Viking heat shield shape. The supersonic parachute design would be identical to MSL. The thermal protection system is projected to be the same as MSL (phenolic impregnated carbon ablator, or PICA).The entry vehicle would be 3-axis controlled during EDL. Gyros within the IMU would be used to propagate 3-axis attitude before and during aero-maneuvering. The IMU and MSL-type descent sensor (for altitude) would be used to trigger parachuting and Sky Crane descent.

Table 3-18. Entry System Mass and Power Preliminary Estimates

	Mass			Average Power		
Flight Element	**CBE (kg)**	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	1381.2	9%	1503.3	0	43%	0
Cabling	5.5	30%	7.2	0	43%	0
Thermal control	23.1	15%	26.5	78	43%	112
Propulsion (dry mass)	0	0%	0	0	43%	0
Attitude control	0	0%	0	0	43%	0
Command and data handling	0	0%	0	0	43%	0
Telecommunications	12.4	10%	13.7	0	43%	0
Power	0	0%	0	0	43%	0
Total flight element dry bus mass	**1422.3**	**9%**	**1550.7**	**4**	**43%**	**6**

Table 3-19. Entry System Characteristics

Flight System Element Parameters (as appropriate)	Value/Summary, units
General	
Design life, months	~ 1 month
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum/titanium/composites
Number of articulated structures	0
Number of deployed structures	2 (parachute and heat shield)
Aeroshell diameter, m	4.7
Thermal Control	
Type of thermal control used	Passive elements (e.g., MLI, thermal conduction control)
Propulsion	N/A
Attitude Control	N/A
Command & Data Handling	N/A
Power	N/A

Cruise Stage

The cruise stage design (Tables 3-20 and 3-21) would take the proposed 2018 mission from launch on a direct flight to Mars atmospheric entry. The cruise stage would release the entry system prior to entry and divert to an atmospheric burn up. The cruise stage would be dead post-separation from the entry system. The cruise stage design has substantial heritage from MSL, which, in turn, derived substantial heritage from Pathfinder and MER. The cruise arrays would be 5.32 m^2 of rigid, triple-junction gallium arsenide (GaAs).

The propulsion system on the cruise stage would consist of eight 4.5N MR-111 thrusters in a double-bowtie configuration to provide spin rate and vector control as well as trajectory correction maneuvers (TCMs). The system design is single fault tolerant and has the ability to isolate a thruster branch in the event of a major thruster leak. The 22 inch titanium diaphragm propellant tanks would be used in blow-down mode and provide approximately 30% propellant capacity margin.

During cruise, the spacecraft would be spin stabilized. There would be no accurate spacecraft attitude control needed since a body-fixed medium-gain antenna would be used. For this reason, there would be no need for reaction wheel for precision attitude control, thereby reducing overall spacecraft mass. Instead, thrusters would be used for rather coarse attitude control if necessary. Sun sensors, star scanner, and IMU telemetry would be sent to the rover flight computer, which processes the data and then commands the thrusters to perform any needed attitude adjustments. Apart from attitude control maneuvers in preparation for TCMs, the cruise stage would typically adjust its attitude to maintain acceptable pointing for solar power generation and DTE communications.

Table 3-20. Cruise Stage Mass and Power Preliminary Estimates

Flight Element	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	217.7	30%	283	0	43%	0
Spacecraft side adapter	45.8	30%	59.5	0	43%	0
Cabling	24.7	30%	32.1	0	43%	0
Thermal control	46.5	7%	49.6	24	43%	34
Propulsion (dry mass)	22.8	9%	24.9	25	43%	36
Attitude control	1.5	5%	1.6	5	43%	7
Command and data handling	1.5	5%	1.6	0	43%	0
Telecommunications	0.7	2%	0.7	15	43%	21
Power	33.1	30%	3.0	20	43%	29
Total flight element dry bus mass	**397.0**	**24%**	**498.7**	–	–	–

Table 3-21. Cruise Stage Characteristics

Flight System Element Parameters (as applicable)	Value/Summary, units
General	
Design life, months	8.3
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum/titanium/composites
Number of articulated structures	0
Number of deployed structures	1 (entry stage)
Aeroshell diameter, m	N/A

Flight System Element Parameters (as applicable)	Value/Summary, units
Thermal Control	
Type of thermal control used	Passive elements
Propulsion	
Estimated delta-V budget, m/s	30
Propulsion type(s) and associated propellant(s)/oxidizer(s)	N_2H_4 propellant
Number of thrusters and tanks	2 propellant tanks
Specific impulse of each propulsion mode, seconds	TCMs and cruise: 228 s ACS: 228 s
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	Spinner
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial
Attitude control capability, degrees	50 arcsec
Attitude knowledge limit, degrees	Not specified in report
Agility requirements (maneuvers, scanning, etc.)	Sun sensors for safe mode
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	0
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	Hydrazine mono-prop thrusters used for stabilization, no RWA system is used
Command & Data Handling	
Flight Element housekeeping data rate, kbps	2 kbits/s
Data storage capacity, Mbits	Uses rover’s CDS
Maximum storage record rate, kbps	Uses rover’s CDS
Maximum storage playback rate, kbps	Not specified in CDS report
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Body mounted
Array size, meters × meters	5.32
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	GaAs triple-junction rigid
Expected power generation at BOL and EOL, watts	BOL = 1587 W, EOL = 653 W
On-orbit average power consumption, watts	~ 250W (peak = 441W)
Battery type (NiCd, NiH, Li-ion)	N/A
Battery storage capacity, amp-hours	N/A

Concept of Operations and Mission Design

The proposed spacecraft would launch as the only payload aboard an Atlas V 531 out of Cape Canaveral, Florida. There is a 20-day launch period, beginning on May 11, 2018 and ending on May 30, 2018. Each day includes one launch opportunity; if needed, a second opportunity may be scheduled each day. More details of each trajectory in the launch period are provided in Table 3-22, and mission design parameters are summarized in Table 3-23. The launch window in each launch opportunity depends on the specific requirements for that day (see the table) as well as the excess launch vehicle capability.

The Atlas V 531 would place the system into a low Earth orbit with an altitude of approximately 185 km. The system would coast to the proper position in the orbit while being tracked from ground stations and GPS. A Centaur upper stage would then perform the trans-Mars injection maneuver, effectively sending the spacecraft system toward Mars. The launch vehicle would bias away from the planet, though, so that no contaminated hardware (e.g., the launch vehicle) lands on the planet.

Table 3-22. Trajectory Parameters for Each Launch Date in the Launch Period

Day	LD	AD	TOF (day)	C3 (km2/sec2	DLA (deg)	RLA (deg)	VHP (km/sec)	DAP (deg)	RAP (deg)	VENTRY (km/sec)	Ls (deg)	SEP (deg)
1	180511	190114	248	8.298	-21.514	337.402	3.356	2.693	242.628	5.96563	323.756	75.196
2	180512	190114	247	8.036	-17.262	334.901	3.372	0.149	243.93	5.97465	323.756	75.196
3	180513	190114	246	7.934	-15.706	333.557	3.376	-0.819	244.515	5.9769	323.756	75.196
4	180514	190114	245	7.87	-14.98	332.537	3.376	-1.319	244.883	5.9769	323.756	75.196
5	180515	190114	244	7.827	-14.619	331.644	3.375	-1.619	245.155	5.97634	323.756	75.196
6	180516	190114	243	7.798	-14.45	330.811	3.372	-1.815	245.374	5.97465	323.756	75.196
7	180517	190114	242	7.782	-14.396	330.008	3.369	-1.949	245.561	5.97295	323.756	75.196
8	180518	190114	241	7.778	-14.415	329.219	3.366	-2.044	245.726	5.97126	323.756	75.196
9	180519	190114	240	7.787	-14.483	328.439	3.363	-2.112	245.874	5.96957	323.756	75.196
10	180520	190114	239	7.807	-14.587	327.662	3.361	-2.162	246.009	5.96844	323.756	75.196
11	180521	190114	238	7.84	-14.716	326.888	3.359	-2.198	246.133	5.96732	323.756	75.196
12	180522	190114	237	7.885	-14.863	326.116	3.357	-2.223	246.248	5.96619	323.756	75.196
13	180523	190114	236	7.942	-15.023	325.346	3.355	-2.24	246.355	5.96507	323.756	75.196
14	180524	190114	235	8.012	-15.192	324.58	3.354	-2.251	246.455	5.96451	323.756	75.196
15	180525	190114	234	8.096	-15.367	323.819	3.353	-2.256	246.548	5.96394	323.756	75.196
16	180526	190114	233	8.192	-15.547	323.064	3.353	-2.257	246.634	5.96394	323.756	75.196
17	180527	190114	232	8.302	-15.728	322.317	3.354	-2.254	246.714	5.96451	323.756	75.196
18	180528	190114	231	8.426	-15.909	321.578	3.354	-2.247	246.789	5.96451	323.756	75.196
19	180529	190114	230	8.564	-16.089	320.851	3.356	-2.238	246.858	5.96563	323.756	75.196
20	180530	190114	229	8.717	-16.267	320.137	3.358	-2.226	246.921	5.96676	323.756	75.196
				8.717						5.9769		

Note: In the table, LD indicates the launch date in the format YYMMDD; AD indicates the arrival date in the format YYMMDD; TOF is the time of flight; C3 is the launch energy; DLA and RLA are the Declination and Right Ascension of the Launch Asymptote; VHP is the hyperbolic excess velocity upon arrival at Mars; DAP and RAP are the Declination and Right Ascension of the Arrival Point; VENTRY is the inertial atmospheric interface velocity; Ls is the location of Mars in its orbit about the Sun; and SEP is the Sun-Earth-Probe angle upon arrival at Mars.

Table 3-23. Mission Design

Parameter	Value	Units
Mission lifetime	16.7 (TBC)	mos
Maximum eclipse period	14	hours (surface)
Launch site	Cape Canaveral	–
Total flight element #1 mass **with** contingency (includes instruments)	4354.4	kg
Propellant mass **without** contingency	103	kg
Propellant contingency	0	%
Propellant mass **with** contingency	103	kg
Launch adapter mass **with** contingency		kg
Total launch mass	4457.4	kg
Launch vehicle	Atlas V 531	type
Launch vehicle lift capability	4980	kg
Launch vehicle mass margin	522.6	kg
Launch vehicle mass margin (%)	11%	%

Once the spacecraft has separated from the upper stage, the spacecraft would perform a maneuver to re-target the proper arrival conditions at Mars. This maneuver would have two purposes: to remove the launch bias and to clean up the launch dispersions. As the spacecraft cruises toward Mars, it would have approximately four more opportunities to perform trajectory adjustments in order to target its entry interface.

The spacecraft would follow a direct, Type I transfer to Mars that requires a duration between 229 and 248 days, arriving at Mars on January 14, 2019. The worst-case launch C3 is 8.717 km^2/s^2 and occurs at the end of the launch period. The worst-case velocity at the atmospheric interface is 5.9769 km/s and occurs near the beginning of the launch period. The spacecraft would arrive at the tail-end of Mars' dust season and land in a region of Mars between latitude 25°N and 15°S.

All tracking and communications between the Earth and the spacecraft during its cruise would be performed with the Deep Space Network (DSN). Tracking would include Doppler and delta-DOR measurements types. The cruise phase tracking would average two passes per week, with increased tracking for the approach and EDL phases. The tracking would use 34m stations, with the exception of the 16 hours around EDL that are planned with a 70m station equivalent. Once the vehicle is on the surface of Mars, communication would include direct communication between the vehicle and the DSN once per day, as well as relay operations to Earth with one or more available Mars orbiters twice per day via a UHF link.

All data associated with major science operations would be relayed to Earth via an orbiter. It is expected that the vehicle would transmit approximately 269.5 Mbits per sol via two passes to the orbiter using the UHF link. The DSN would transmit daily commands to the vehicle directly across the X-band link; the commands and file updates would not exceed ~3.5 Mbits per day. In addition, once per month the Earth would update the vehicle's clock and perform other routine updates.

The data would be at least 95% complete with latency no longer than 7 sols. Limited, critical data would be ~99.9% complete. Typical latency for data would be on the order of 24 hours; some data types, e.g., driving, would have a shorter average latency time of approximately 12 hours.

The operations would be a mission-specific implementation of the JPL mission operations and ground systems as used previously for MSL (Table 3-24). Standard JPL operations processes and procedures would be used. The different configurations and instruments on the rover and substation package would require new spacecraft models and flight rules to support sequence tools, as well as new telemetry formats.

The operations support would be 24/7 for the first 90 days, shifting to regular work weeks for the remainder of the surface science operations. The mission operations would include processing to Level 0 data and maintaining it for the life of the mission. Further processing and archiving would be the responsibility of the science operations. The operations are assumed to be conducted at JPL.

Table 3-24. Mission Operations and Ground Data Systems

Support Period		Antenna	Service	Hours per	No. Tracks	No. Weeks
No	Name	Size	Year	Track	per Week	Required
(#)	(description)	(meters)	(year)	(hours)	(# tracks)	(# weeks)
1	Launch and Operations	34BWG	2018	8	21.0	2.0
2	Launch and Operations	34BWG	2018	8	14.0	2.0
3	Cruise- Cruise	34BWG	2018	8	2.0	24.0
4	Cruise- approach hvy	34BWG	2018	8	21.0	3.0
4	DDOR	34BWG	2018	1	4.0	3.0
5	Cruise- approach lt	34BWG	2018	8	14.0	3.0
5	DDOR	34BWG	2018	1	3.0	3.0
6	Deployment & checkout- DTE	34BWG	2018	0.5	7.0	13.0
6	Relay	34BWG	2018	0.5	14.0	13.0
7	Roving and science operation	34BWG	2018	0.5	7.0	66.0
7	Relay	34BWG	2018	0.5	14.0	66.0
8	EDL	70	2018	8	2.0	1.0
8	EDL	34BWG	2018	1	7.0	1.0
8	Relay	34BWG	2018	0.3	12.0	1.0

Round-Trip Planetary Protection

The proposed 2018 MAX-C/ExoMars mission is expected to be categorized as Class IVa overall and Class IVb for the sampling system. Forward planetary protection technologies developed over the past decade for MER, Phoenix, and MSL missions would be adequate to satisfy the anticipated MAX-C mission concept's forward planetary protection requirements, i.e., to protect Mars from forward

contamination from Earth. However, since the MAX-C mission concept plans to assemble a cache of samples with the intent that it would be returned by a potential future Mars sample return mission, the samples and the associated hardware would have an additional requirement to be kept free of “round-trip” Earth organisms that could interfere with biohazard and life-detection testing of martian samples upon return to Earth. There are two distinct approaches to meeting the stringent planetary protection requirements for round-trip planetary protection: (1) system sterilization and (2) component- and subsystem-level sterilization, along with associated bio-barriers. The component- and subsystem-level sterilization approach is less costly to develop. Many technologies required for this approach have been developed to mid-TRL maturities. The overall maturity level for this capability is TRL 4. Backward planetary protection (the prevention of Mars organisms from entering Earth's biosphere) would be addressed by the follow-on sample return missions.

Risk List

The following chart provides an overview of mission and programmatic risks that have been identified. Each risk is scored by the sub-system(s) that are affected by it and subsequently given a final score by the study risk engineer. A risk identified as High (red) suggests the need to implement a new process or processes, Medium (yellow) suggests the need to aggressively manage the issue or, possible, to consider an alternative process, and Low (green) suggests the need to monitor the issue regularly. The 5×5 chart (Figure 3-4) summarizes the number of risks identified in each category.

Each of the risks identified for this mission was categorized as either a mission risk, implementation risk, or both. A risk is a mission risk if the impact of the negative event affects the percentage of mission objectives completed (i.e., a 5 = mission failure), and it is an implementation risk if the impact affects the consumption of resources (i.e., a 4 = all resources, including contingencies, would be consumed). Table 3-25 provides the definitions used to place each identified risk.

The following risks have been identified:

1) Development challenge of matching MSL landing hazard tolerance, requiring either active hazard avoidance on landing or a robust pallet with level and egress mechanism, or some combination of both. Likelihood: 4, Consequence: 4, Mitigation: Expect to retire risk via pre-project technology investment.

2) Significant planetary protection activities might be required due to either proposed MAX-C sample caching requirement or ExoMars in situ science objectives. Likelihood: 3, Consequence: 3, Mitigation: Expect to retire risk via pre-project technology investment.

3) MSL heritage hardware might be more expensive/difficult to replicate than assumed (Mars lander engine (MLE), high-flow pressure regulator, radar). Likelihood: 4, Consequence: 3, Mitigation: Develop cost commitments/alternate suppliers during Pre-Phase A/Phase A.

4) Instruments require independently funded technology maturation prior to release of the announcement of opportunity (AO). Likelihood: 3, Consequence: 3, Mitigation: Careful evaluation during AO selection; consider early selection and fund risk-reduction activities post-selection.

5) Development challenge of realizing coring/caching capability that would meet requirements within scoped resources could ripple significantly into the system design. Likelihood: 3, Consequence: 4, Mitigation: Expect to retire risk via pre-project technology investment.

6) Potential evolving planetary protection requirements might require the spacecraft to meet more stringent bioburden limits. Likelihood: 2, Consequence: 5, Mitigation: Must meet planetary protection requirements to launch.

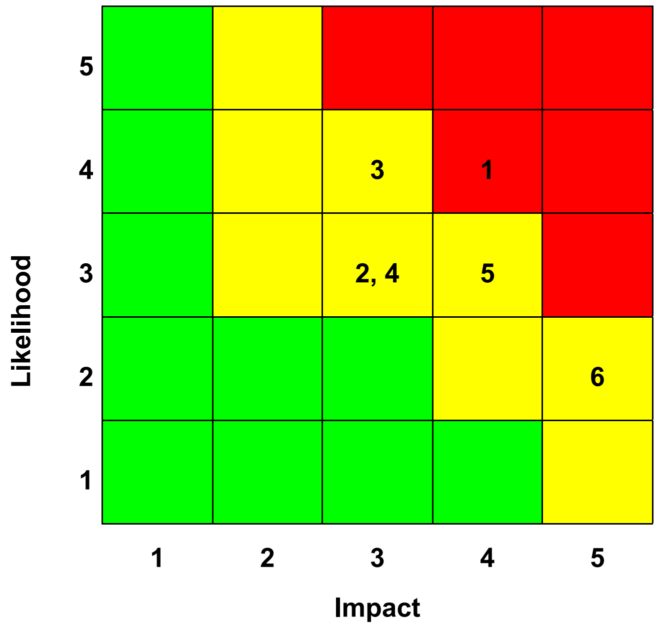


Figure 3-4. Risk Chart

Table 3-25. Risk Level Definitions

Levels	Mission Risk		Implementation Risk	
	Impact	**Likelihood of Occurrence**	**Impact**	**Likelihood of Occurrence**
5	Mission failure	Very high, ~10%	Consequence or occurrence is not repairable without engineering (would require >100% of margin)	Very high, ~70%
4	Significant reduction in mission return (~10% of mission return still available)	High, ~5%	All engineering resources will be consumed (100% of margin consumed)	High, ~50%
3	Moderate reduction in mission return (~50% of mission return still available)	Moderate, ~1%	Significant consumption of engineering resources (~50% of margin consumed)	Moderate, ~30%
2	Small reduction in mission return (~90% of mission return still available)	Low, ~0.5%	Small consumption of engineering resources (~10% of margin consumed)	Low, ~10%
1	Minimal (or no) impact to mission (~99% of mission return still available)	Very low, ~0.1%	Minimal consumption of engineering resources (~1% of margin consumed)	Very low, ~1%

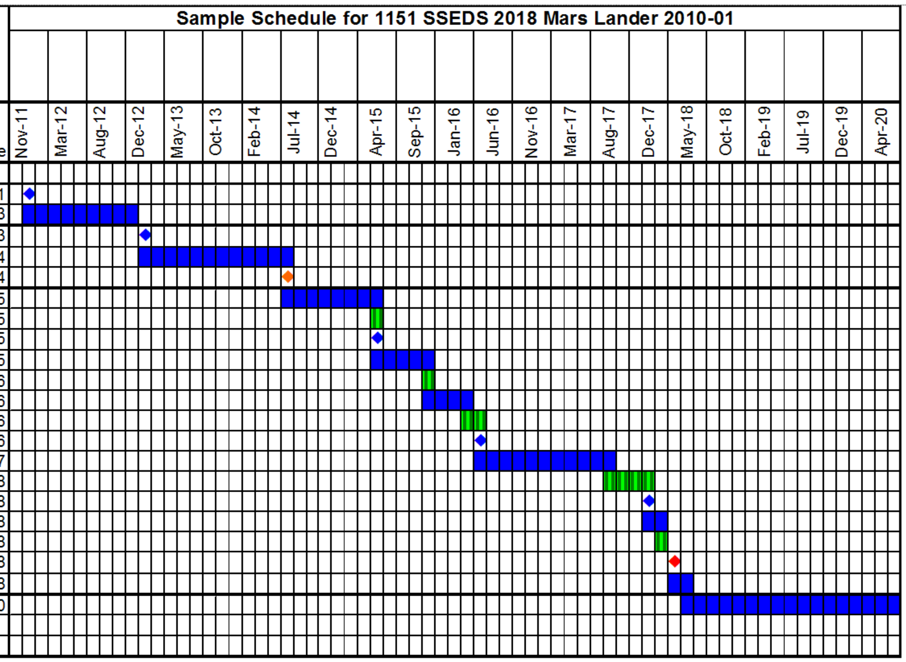
4. Development Schedule and Schedule Constraints

High-Level Mission Schedule

The proposed MAX-C mission schedule is summarized in Tables 4-1 and 4-2.

Table 4-1. High-Level Mission Schedule

Complex Mission (Cutting edge technology (SIM) or highly complex payloads and mission (Cassini, MSL, etc)		
Phase	Start Date	End Date
1151 SSEDS 2018 Mars Lander 2010-01		
MCR	12/20/11	12/22/11
Ph A Project Definition	12/20/11	02/12/13
PMSR	02/20/13	02/22/13
Ph B Preliminary Design	02/25/13	07/20/14
CR/PDR/Tech Cutoff	07/20/14	07/23/14
Ph C Design	07/20/14	06/15/15
Margin	06/15/15	07/20/15
CDR	07/20/15	07/23/15
Ph C Fabrication	07/23/15	12/21/15
Margin	12/21/15	01/04/16
Ph C S/S I&T	01/04/16	06/03/16
Margin	06/03/16	06/20/16
ARR (ph D)	06/20/16	06/23/16
Proj I&T (ATLO)	06/23/16	11/05/17
Margin	11/05/17	02/20/18
PSR	02/20/18	02/23/18
Launch Ops	02/23/18	05/03/18
Margin	05/03/18	05/20/18
Launch	05/20/18	06/10/18
L+30-end Ph D	06/10/18	07/10/18
Phase E	07/10/18	07/29/20



Legend	
Normal Task	
Margin	
Long Lead Item	
Project Level Review	◆◆◆
PDR/Tech cutoff	◆◆◆
Launch	◆◆◆

Table 4-2. Key Phase Duration

Project Phase	Duration (Months)
Phase A – Conceptual Design	14
Phase B – Preliminary Design	17
Phase C – Detailed Design	23
Phase D – Integration & Test	24
Phase E – Primary Mission Operations	25
Phase F – Extended Mission Operations	0
Start of Phase B to PDR	17
Start of Phase B to CDR	29
Start of Phase B to Delivery of Instrument #1	N/A

Project Phase	Duration (Months)
Start of Phase B to Delivery of Instrument #2	N/A
Start of Phase B to Delivery of Instrument #n	N/A
Start of Phase B to Delivery of Flight Element #1	N/A
Start of Phase B to Delivery of Flight Element #2	N/A
Start of Phase B to Delivery of Flight Element #n	N/A
System-Level Integration & Test	20
Project Total Funded Schedule Reserve	6.5
Total Development Time Phase B - D	64

Technology Development Plan

This section provides the technology development plans for technologies identified in Section 2. The development costs are shown in Table 4-3 and Section 5.

Table 4-3. Technology Development Cost Profile

Focused Technology	FY'11, RY$M	FY'12, RY$M	FY'13, RY$M	FY'14, RY$M	Total, RY$M
Sample Acquisition	2.5	6	9	6	23.5
Round-Trip Planetary Protection	0.5	3	5.5	5	14
Mobility	2.5	6	5.5	5	19
Terrain-Relative Descent Navigation	2	5	8	8.5	23.5
Total	**7.5**	**20**	**28**	**24.5**	**80**

Note: Development costs are in real year dollars (millions), including 50% reserve

Sample Acquisition and Encapsulation

Four end-to-end sample acquisition and encapsulation concepts are currently being developed by industry and JPL. The first phase has been completed. The second phase started in February 2010 and will complete by the end of September 2010. This phase will include fabrication of the coring tool and caching subsystem. After this phase, the subsystems will be integrated onto a rover for testing in the laboratory and field. The Mars Exploration Program will select an approach that is most suitable for the proposed MAX-C rover and its constraints. Focused technology will develop this capability to TRL 6 by MAX-C mission PDR, starting in early FY 11. The development will consist of system trades; component technology development and testing; system integration; and laboratory, Mars Yard, and field testing.

Terrain-Relative Descent Navigation and Precision Landing

The ongoing terrain relative descent navigation technology development is a multi-year year task which is part of the Autonomous Landing and Hazard Avoidance Technology program lead by Johnson Space Center (JSC) with support from JPL, Langley Research Center, the Charles Stark Draper Laboratory, and the Applied Physics Laboratory. Portions of this technology development will be leveraged to develop a point design for the proposed MAX-C mission. The safe landing approach for the MAX-C mission would use a camera to image the landing site when the lander is a few kilometers above the surface. These images will be registered and compared with the orbital images of the landing site that are on-board the lander as the spacecraft prepares to land. This would provide the true coordinates of the lander relative to the surface. The onboard computer would then compute an optimal (i.e., minimal fuel) trajectory to land on the nearest safe location designated on the map. This technology development will focus on the development of a camera with fast image transfer and processing capability, map development, image registration, and optimal descent trajectory development. The development will start in early FY 11. System trades will be performed in the first 9 months. Subsystems will be developed and tested via

simulation and field testing. Then the system will be integrated and helicopter tests will be performed to assess the performance of the system by comparing the spacecraft location with data from GPS. The technology plan would be to develop this capability to TRL 6 by MAX-C mission PDR.

Mobility Increasing the Average Rover Speed

To increase the average speed of the proposed MAX-C rover, a co-processor subsystem using field-programmable gate arrays (FPGAs) would be utilized. This effort will leverage a technology task at JPL that has developed and demonstrated fast stereo image processing using FPGAs, as well as a current on-going technology task to develop and implement the initial architecture for increasing the average rover speed. The objective is to be able to run all the autonomy-related routines, including hazard detection/avoidance and visual odometry, in near real time so that the rover would not stop for each move, except perhaps for short periods for turns if the control hardware is not able to control all the wheel motors simultaneously. More specifically, the technology development plan will consist of the following tasks: 1) Implement FPGA versions of stereo, visual odometry, and autonomous navigation to enable the MAX-C rover to perform fast and power-efficient continuous driving with the same average traverse speed and power efficiency as exists currently for blind/directed driving, 2) demonstrate those implementations on a research rover using commercial, off-the-shelf FPGA electronics, 3) derive, document, and communicate the insights garnered and quantitative measurements made during implementation, and 4) thoroughly test the capability via Mars Yard and field tests. This plan is to develop this capability to TRL 6 by the MAX-C mission PDR.

Reducing Control Electronics Volume and Mass

A distributed motor control capability will be developed by utilizing the thermal cycle resistance electronics technology developed for MSL and leveraging an Exploration Technology Development Program technology effort to develop small, credit card–size processing boards that can perform low-level closed-loop motor control functions that are located near the rover motors. A study is currently under way to perform trades and prepare detailed technology development plans for an early start in FY 11; the study will include ASIC vs. FPGA development trades. Life testing will be performed to support the proposed MAX-C rover’s 500-sol design, or 1500 cycles. Technology will be developed to TRL 6 by mission PDR.

Round-Trip Planetary Protection

The technology development for round-trip planetary protection would start in early 2011. A computer modeling tool that was developed by the Mars Technology Program in 2008 will be updated to account for all possible sources of sample contamination by Earth organisms. This computer model will be very specific to overall mission architecture, including the existence of bio-barriers, and the specific architecture of the sampling system. Analysis and experiments will be conducted to estimate the probability of contamination for each subsystem. Early effort in this area will identify those subsystems that are critical to reducing the probability of contaminations. This information will be used to modify subsystem designs such that the overall requirement for avoiding Earth organism contamination is reduced to the acceptable level. Round-trip planetary protection capability to satisfy the requirements will be developed to TRL 6 by the mission PDR.

Instruments

Both the Raman and NIR spectrometers are being developed under the NASA Planetary Instrument Definition and Development Program.

Development Schedule and Constraints

Technologies and development have been planned in the schedule to be completed prior to the MAX-C mission PDR, and development schedules have been coordinated with the ExoMars team. Should the spacecraft not be ready for launch, the mission would be slipped to the following launch opportunity. Launch opportunities for the proposed MAX-C mission occur roughly every 26 months.

5. Mission Life-Cycle Cost

Costing Methodology and Basis of Estimate

JPL's Advanced Projects Design Team (Team X) generates a most likely cost for the JPL standard WBS that may be tailored to meet the specific needs of the mission being evaluated. These estimates are done at Work Breakdown Structure (WBS) levels 2 and 3 and are based on various cost estimating techniques. These methods are not exclusive to each other and are often combined. The various estimating techniques consist of grassroots techniques, parametric models, and analogies. The models for each station at Team X have been built (total of about 33) and validated, and they are each owned by the responsible line organization. The models are under configuration management control and are utilized in an integrated and concurrent environment, so the design and cost parameters are linked. These models are customized and calibrated using actual experience from completed JPL planetary missions. In applying these models it has been found that the resultant total estimated Team X mission costs have been consistent with mission actual costs.

The cost estimation process begins with the customer providing the base information for the cost estimating models and defining the mission characteristics, such as:

- Mission architecture
- Payload description
- Master equipment list (MEL) with heritage assumptions
- Functional block diagrams
- Spacecraft/payload resources [MEL, mass (kg), power (W), …]
- Phase A–F schedule
- Programmatic requirements
- Model specific inputs

Most of the above inputs are provided by the customer through a Technical Data Package.

For Decadal Survey missions, the following specific guidelines were also followed:

- Reserves were set at 50% for Phases A– D
- Reserves were set at 25% for Phase E.
- The launch vehicle cost was provided by the customer.
- Costs for the advanced Stirling radioisotope generator were also provided by the customer.

Costs for technology development were estimated by the team outside of Team X. The technologies that were studied were sample acquisition, EDL technology with hazard avoidance and precision landing, mobility with autonomy and distributed motor control, and forward planetary protection.

Cost Estimates

Tables 5-1 and 5-2 contain costs and workforce by phase for all science activities for the mission.

Table 5-1. Science Costs and Workforce

	A	B	C	D	E	F	Total	ABCD SUM
	$K	$K	$K	$K	$K	$K	$K	$K
Science	860.7	4622.9	17268.6	16766.2	24934.1	3708.9	68161.3	39518.3
Science Management	255.5	1388.0	1998.0	2564.9	2519.8	540.0	9266.3	6206.5
Science Office	255.5	1388.0	1998.0	2564.9	2519.8	540.0	9266.3	6206.5
Science Implementation	508.2	2180.5	13232.9	10109.3	19196.3	2479.3	47706.5	26030.9
Participating Scientists	129.5	157.2	817.2	1491.6	3174.9	680.3	6450.9	2595.6
Teams Summary	378.7	2023.3	12415.7	8617.7	16021.3	1799.0	41255.6	23435.3
Science Support	97.0	1054.3	2037.6	4092.0	3218.1	689.6	11188.6	7280.9
Science Data Visualization	24.5	59.4	80.4	97.8	73.4	15.7	351.2	262.1
Science Data Archiving	0.0	247.5	334.9	875.9	1222.9	262.1	2943.2	1458.2
Instrument Support	0.0	455.0	615.6	996.4	1080.8	231.6	3379.4	2066.9
Science Environmental Characterization	43.7	257.4	959.5	1940.8	149.2	32.0	3382.6	3201.4
Operations Support	28.8	35.0	47.4	181.2	691.7	148.2	1132.3	292.3

	A	B	C	D	E	F	Total	Total
	W-M	W-M	W-M	W-M	W-M	W-M	W-M	W-Y
Science	**24.0**	**159.5**	**684.6**	**651.3**	**1017.8**	**147.1**	**2684.2**	**223.7**
Science Management	6.2	32.6	50.3	66.4	73.0	15.6	244.1	20.3
Science Office	6.2	32.6	50.3	66.4	73.0	15.6	244.1	20.3
Science Implementation	14.3	80.6	547.5	411.1	800.9	100.6	1955.0	162.9
Participating Scientists	4.9	6.0	31.6	58.6	127.7	27.4	256.2	21.3
Teams Summary	9.4	74.6	515.8	352.4	673.2	73.3	1698.8	141.6
Science Support	3.5	46.3	86.8	173.8	143.9	30.8	485.1	40.4
Science Data Visualization	1.1	2.6	3.5	4.2	3.2	0.7	15.1	1.3
Science Data Archiving	0.0	10.6	14.4	37.6	52.5	11.3	126.4	10.5
Instrument Support	0.0	22.1	29.9	48.4	52.5	11.3	164.2	13.7
Science Environmental Characterization	1.1	9.4	36.8	74.8	2.1	0.5	124.6	10.4
Operations Support	1.4	1.7	2.3	8.8	33.6	7.2	55.0	4.6

Phase A is 15 months long, and is estimated to cost $43.5M.

Table 5-2. Total Mission Cost Funding Profile

(FY costs in Real Year Dollars, Totals in Real Year and 2015 Dollars)

Item	FY2011	FY2012	FY2013	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	Total (Real Yr.)	Total (FY 2015)
Cost												
Phase A Concept Study (included below)		27.0	13.4								40.4	43.5
Technology Development (w/ Reserves)	9.8	17.4	28.3	24.3							79.8	84.4
Mission PM/SE/MA		0.9	5.8	13.6	33.0	33.9	34.8	25.5			147.5	144.5
Instrument PM/SE		0.1	0.9	2.1	5.0	5.1	5.3	3.9			22.4	21.9
Pancam (Mast, Phoenix, MER)		0.0	0.2	0.5	1.1	1.1	1.2	0.8			4.9	4.8
NIR point spectrometer (Mast)		0.1	0.7	1.6	3.8	3.9	4.0	2.9			16.9	16.6
Raman Spectrometer (Body)		0.3	2.0	4.7	11.4	11.7	12.0	8.8			50.8	49.8
APXS (Mast, MSL)		0.0	0.2	0.5	1.3	1.3	1.3	1.0			5.6	5.5
Microscopic imager (Arm) MI design		0.0	0.2	0.5	1.3	1.3	1.4	1.0			5.8	5.7
Flight PM/SE		0.4	2.3	5.5	13.3	13.6	14.0	10.3			59.4	58.1
Rover		1.8	11.9	27.9	67.9	69.6	71.4	52.4			303.0	296.8
Landing Pallet		0.3	1.7	4.0	9.7	10.0	10.3	7.5			43.5	42.6
Descent		1.1	7.0	16.3	39.5	40.6	41.6	30.5			176.5	172.9
Entry		0.6	3.9	9.1	22.2	22.8	23.4	17.1			99.2	97.1
Cruise		0.5	3.0	7.1	17.2	17.7	18.1	13.3			77.0	75.4
ATLO		0.4	2.5	5.9	14.2	14.6	15.0	11.0			63.6	62.3
Mission Ops Dev		0.2	1.1	2.7	6.5	6.6	6.8	5.0			28.9	28.3
Pre-launch Science		0.3	1.8	4.2	10.3	10.6	10.9	8.0			46.1	45.1
Ground Data System Dev		0.2	1.3	2.9	7.1	7.3	7.5	5.5			31.8	31.1
Total Dev. w/o Reserves	9.8	24.6	74.9	133.3	264.9	271.8	278.9	204.5			1262.7	1242.9
Development Reserves		3.7	23.7	55.4	134.8	138.3	141.9	104.0			601.8	589.4
Total A-D Development Cost	9.8	28.3	98.6	188.7	399.7	410.1	420.8	308.5			1864.5	1832.3
Launch services				11.3	57.4	58.9	60.4	44.3			232.3	247.6
Phase E Science								4.7	17.2	14.5	36.3	32.7
Other Phase E Cost								5.6	20.7	17.4	43.6	39.3
Phase E Reserves								2.9	10.7	9.0	22.6	20.4
Mars Program Cost	9.8	28.3	98.6	200.0	457.1	469.0	481.2	365.9	48.6	40.9	2199.3	2172.4
Education/Outreach		0.0	0.1	0.3	0.7	0.7	0.8	1.9	5.0	4.2	13.7	12.6
DSN		0.0	0.1	0.2	0.5	0.5	0.5	1.7	5.0	4.2	12.6	11.5
Total NASA Cost	$9.8	$28.3	$98.9	$200.5	$458.3	$470.2	$482.4	$369.5	$58.5	$49.2	$2,225.6	$2,196.5
									Total Mission Cost (FY2015)			$2,196.5

The profile in Table 5-2 is model based and not necessarily what the program has proposed. Due to the nature of the international partnership and the accelerated development schedule of the ExoMars rover, a slightly modified profile has been developed by the program to provide advanced funding for early interface definition. This program office recommended profile is shown below.

Year	FY2011	FY2012	FY2013	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	Total (RY)
Program Recommended Profile	$15.0	$38.0	$129.0	$265.0	$356.0	$484.0	$462.0	$333.0	$83.0	$60.0	$2,225.0

Appendix A. Acronym List

AO	announcement of opportunity
APXS	Alpha Particle X-ray Spectrometer
ASIC	application-specific integrated circuit
BOL	beginning of life
CAT	Honeybee Corer-Abrader Tool
CBE	current best estimate
CCD	charge-coupled device
CDR	critical design review
CDS	command and data subsystem
CML	concept maturity level
cont.	contingency
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
DOF	degrees of freedom
DOR	differential one-way ranging
DSN	Deep Space Network
DTE	direct-to-Earth
EDL	entry, descent, and landing
EOL	end of life
ESA	European Space Agency
FOV	field of view
FPGA	field-programmable gate array
GaAs	gallium arsenide
GPS	global positioning system
HFPR	high-flow pressure regulator
HGA	high-gain antenna
IMU	inertial measurement unit
IR	Infrared
JPL	Jet Propulsion Laboratory
LGA	low-gain antenna
Li-ion	lithium ion
M3	Moon Mineralogy Mapper
MAX-C	Mars Astrobiology Explorer-Cacher
MEL	master equipment list
MEP	Mars Exploration Program
MER	Mars Exploration Rover
MEV	maximum expected resource value
MI	Microscopic Imager
MLE	Mars lander engine
MLI	multi-layer insulation
MOLA	Mars Orbiter Laser Altimeter
MSL	Mars Science Laboratory
NiCd	nickel cadmium
NiH	nickel hydride
NIR	near infrared
N_2H_4	hydrazine
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
PDR	preliminary design review
PICA	phenolic impregnated carbon ablator
RAT	rock abrasion tool
RHU	radioisotope heater unit
RWA	reaction wheel assembly
SDST	small deep space transponder
SHEC	Sample Handling, Encapsulation, and Containerization
Si	silicon
SWIR	short-wave infrared
TCM	trajectory correction maneuver
Team X	JPL Advanced Project Design Team
TRL	technology readiness level
UHF	ultra-high frequency
UV	ultraviolet
Vis	visible
WBS	work breakdown structure
WEB	warm electronics box

Appendix B. Master Equipment Lists

The following MELs are included in this appendix:

- Cruise Stage
- Entry System
- Descent Stage
- Pallet
- MAX-C Rover

Cruise Stage MEL

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Launch Mass			**4347.8 kg**	**2%**	**4449.5 kg**
Launch Vehicle PLA			**0.0 kg**	**30%**	**0.0 kg**
Stack (w/ Wet Element)			**4347.8 kg**	**2%**	**4449.5 kg**
Useable Propellant			**103.0 kg**	**0%**	**103.0 kg**
Stack (w/ Dry Element)			**4244.8 kg**	**2%**	**4346.5 kg**
Carried Elements			**3847.8 kg**	**0%**	**3847.8 kg**
MAX-C Rover			364.5 kg	0%	364.5 kg
EXO-Mars Rover			300.0 kg	0%	300.0 kg
Pallet			327.5 kg	0%	327.5 kg
Descent Stage			1305.2 kg	0%	1305.2 kg
Entry System			1550.7 kg	0%	1550.7 kg
Dry Element			**397.0 kg**	**26%**	**498.7 kg**
Wet Element			**500.0 kg**	**20%**	**601.7 kg**
Useable Propellant			**103.0 kg**	**0%**	**103.0 kg**
System 1: Monoprop			**103.0 kg**	**0%**	**103.0 kg**
Dry Element			**397.0 kg**	**26%**	**498.7 kg**
System Contingency			**0.0 kg**	**0%**	
Subsystem Heritage Contingency			**101.7 kg**	**26%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**397.0 kg**	**26%**	**498.7 kg**
Attitude Control		**16**	**1.5 kg**	**5%**	**1.6 kg**
Sun Sensor 1	0.0 kg	14.0	0.1 kg	5%	0.1 kg
Star Tracker 1	1.5 kg	1.0	1.5 kg	5%	1.5 kg
Command & Data		**2**	**1.5 kg**	**5%**	**1.6 kg**
Analog_I_F: MREU	0.8 kg	1	0.8 kg	5%	0.9 kg
Custom_Special_Function_Board: TMC	0.7 kg	1	0.7 kg	5%	0.7 kg
Power		**15**	**33.1 kg**	**30%**	**43.0 kg**
GaAs TJ Rigid Solar Array (5.32311846200207 m^2)	7.6 kg	1	7.6 kg	30%	9.9 kg
Chassis	3.9 kg	1	3.9 kg	30%	5.1 kg
Array Segment Switches* Boards	2.2 kg	2	4.4 kg	30%	5.8 kg
Load Switches Boards	1.0 kg	4	4.0 kg	30%	5.2 kg
Thruster Drivers* Boards	1.1 kg	2	2.2 kg	30%	2.9 kg
Houskeeping DC-DC Converters* Boards	1.1 kg	2	2.3 kg	30%	2.9 kg
Power/Shunt Control* Boards	4.0 kg	2	8.0 kg	30%	10.4 kg
Shielding	0.6 kg	1	0.6 kg	30%	0.8 kg
Propulsion		**54**	**25.5 kg**	**8%**	**27.6 kg**
System 1: Monoprop		54	25.5 kg	8%	27.6 kg
Hardware		54	22.8 kg	9%	24.9 kg
Gas Service Valve	0.2 kg	2	0.5 kg	2%	0.5 kg
Temp. Sensor	0.0 kg	1	0.0 kg	5%	0.0 kg
Liq. Service Valve	0.3 kg	1	0.3 kg	2%	0.3 kg
LP Transducer	0.3 kg	2	0.5 kg	2%	0.6 kg
Liq. Filter	0.4 kg	1	0.4 kg	2%	0.4 kg
LP Latch Valve	0.4 kg	2	0.7 kg	2%	0.7 kg
Temp. Sensor	0.0 kg	34	0.3 kg	5%	0.4 kg
Lines, Fittings, Misc.	3.0 kg	1	3.0 kg	10%	3.3 kg
Monoprop Main Engine	0.4 kg	8	3.0 kg	10%	3.3 kg
Fuel Tanks	7.0 kg	2	14.1 kg	10%	15.5 kg
Pressurant			0.2 kg	0%	0.2 kg
Residuals			2.5 kg	0%	2.5 kg

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Cruise Stage MEL (continued)

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Mechanical		**11**	**288.2 kg**	**30%**	**374.7 kg**
Struc. & Mech.		9	217.7 kg	30%	283.0 kg
Primary Structure	100.6 kg	1	100.6 kg	30%	130.8 kg
Secondary Structure	21.8 kg	1	21.8 kg	30%	28.3 kg
Solar Array Structure	7.5 kg	1	7.5 kg	30%	9.7 kg
Thruster Support Structure	5.2 kg	1	5.2 kg	30%	6.8 kg
Prop Support Structure	3.0 kg	1	3.0 kg	30%	3.9 kg
Radiator Panels	53.1 kg	1	53.1 kg	30%	69.0 kg
Separation Devices	16.3 kg	1	16.3 kg	30%	21.2 kg
Cruise Stage PAI &CM	9.9 kg	1	9.9 kg	30%	12.9 kg
Purge Hardware	0.4 kg	1	0.4 kg	30%	0.6 kg
Adapter, Spacecraft side	45.8 kg	1	45.8 kg	30%	59.5 kg
Cabling Harness	24.7 kg	1	24.7 kg	30%	32.1 kg
Telecom		**2**	**0.7 kg**	**2%**	**0.7 kg**
X-MGA (19dB) MER	0.4 kg	1	0.4 kg	2%	0.4 kg
Other	0.3 kg	1	0.3 kg	2%	0.3 kg
Thermal		**63**	**46.5 kg**	**7%**	**49.6 kg**
Multilayer Insulation (MLI)	2.1 kg	5	10.3 kg	15%	11.8 kg
Thermal Conduction Control		1	0.5 kg	15%	0.6 kg
General	0.5 kg	1	0.5 kg	15%	0.6 kg
Other Components		10	35.8 kg	4%	37.2 kg
CIPAS	22.7 kg	1	22.7 kg	2%	23.1 kg
HRS Tube Assy	6.1 kg	1	6.1 kg	5%	6.4 kg
HRS CFC-11	6.3 kg	1	6.3 kg	10%	7.0 kg
HRS Tube Epoxy	0.2 kg	1	0.2 kg	20%	0.2 kg
Fluid (P-Clamp+Bulk Jam Nut)	0.5 kg	1	0.5 kg	5%	0.5 kg

Entry System MEL

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Entry Mass			**3719.5 kg**	**3%**	**3847.8 kg**
Stack (w/ Wet Element)			**3719.5 kg**	**3%**	**3847.8 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**3719.5 kg**	**3%**	**3847.8 kg**
Carried Elements			**2297.2 kg**	**0%**	**2297.2 kg**
MAX-C Rover			364.5 kg	0%	364.5 kg
EXO-Mars Rover			300.0 kg	0%	300.0 kg
Pallet			327.5 kg	0%	327.5 kg
Descent Stage			1305.2 kg	0%	1305.2 kg
Dry Element			**1422.3 kg**	**9%**	**1550.7 kg**
Wet Element			**1422.3 kg**	**9%**	**1550.7 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**1422.3 kg**	**9%**	**1550.7 kg**
System Contingency			**0.0 kg**	**0%**	
Subsystem Heritage Contingency			**128.4 kg**	**9%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**1422.3 kg**	**9%**	**1550.7 kg**
Attitude Control		**1**	**0.0 kg**	**0%**	**0.0 kg**
Command & Data		**0**	**0.0 kg**	**0%**	**0.0 kg**
Power		**2**	**0.0 kg**	**0%**	**0.0 kg**
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**6**	**1386.8 kg**	**9%**	**1510.4 kg**
Struc. & Mech.		5	1381.2 kg	9%	1503.3 kg
Backshell	533.0 kg	1	533.0 kg	10%	586.3 kg
Heatshield	462.6 kg	1	462.6 kg	10%	508.8 kg
Parachute	88.2 kg	1	88.2 kg	5%	92.6 kg
Cruise Ballast	138.7 kg	1	138.7 kg	5%	145.6 kg
Entry Ballast	158.8 kg	1	158.8 kg	7%	169.9 kg
Cabling Harness	5.5 kg	1	5.5 kg	30%	7.2 kg
Telecom		**17**	**12.4 kg**	**10%**	**13.7 kg**
X-LGA MER/MPF CWG	0.4 kg	2	0.8 kg	2%	0.8 kg
UHF-MGA array	7.9 kg	1	7.9 kg	7%	8.4 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	2	0.9 kg	2%	0.9 kg
Polarizer	0.3 kg	2	0.5 kg	25%	0.7 kg
Other	0.1 kg	2	0.1 kg	30%	0.1 kg
Other	0.0 kg	2	0.1 kg	10%	0.1 kg
WR-112 WG, rigid (Al)	0.5 kg	4	1.8 kg	30%	2.3 kg
Coax Cable, flex (190)	0.3 kg	1	0.3 kg	2%	0.3 kg
Coax Cable, flex (120)	0.1 kg	1	0.1 kg	2%	0.1 kg
Thermal		**57**	**23.1 kg**	**15%**	**26.5 kg**
Multilayer Insulation (MLI)	2.1 kg	10	20.5 kg	15%	23.6 kg
Thermal Conduction Control		1	1.6 kg	0%	1.6 kg
General	1.6 kg	1	1.6 kg	0%	1.6 kg
Other Components		1	1.0 kg	30%	1.3 kg
Ext SLI	1.0 kg	1	1.0 kg	30%	1.3 kg

(End of Entry System MEL)

Descent Stage MEL

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Descent Mass			**2171.5 kg**	**6%**	**2305.0 kg**
Stack (w/ Wet Element)			**2171.5 kg**	**6%**	**2305.0 kg**
Useable Propellant			**493.0 kg**	**0%**	**493.0 kg**
Stack (w/ Dry Element)			**1678.5 kg**	**8%**	**1812.1 kg**
Carried Elements			**992.0 kg**	**0%**	**992.0 kg**
MAX-C Rover			364.5 kg	0%	364.5 kg
EXO-Mars Rover			300.0 kg	0%	300.0 kg
Pallet			327.5 kg	0%	327.5 kg
Dry Element			**686.5 kg**	**19%**	**820.1 kg**
Wet Element			**1179.5 kg**	**11%**	**1313.0 kg**
Useable Propellant			**493.0 kg**	**0%**	**493.0 kg**
System 1: Monoprop			**493.0 kg**	**0%**	**493.0 kg**
System 2: 0			**0.0 kg**	**0%**	**0.0 kg**
System 3: 0			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**686.5 kg**	**19%**	**820.1 kg**
System Contingency			**0.0 kg**	**0%**	
Subsystem Heritage Contingency			**133.5 kg**	**19%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**686.5 kg**	**19%**	**820.1 kg**
Attitude Control		**5**	**49.4 kg**	**3%**	**50.8 kg**
IMU 1	4.0 kg	1.0	4.0 kg	5%	4.2 kg
Terminal Descent Sensor	23.6 kg	1.0	23.6 kg	2%	24.1 kg
Descent Motor Controller	18.4 kg	1.0	18.4 kg	2%	18.8 kg
Integrated sensor suite for image correlation based hazard reduction	3.4 kg	1.0	3.4 kg	10%	3.7 kg
Command & Data		**2**	**1.5 kg**	**11%**	**1.7 kg**
Analog_I_F: MREU	0.8 kg	1	0.8 kg	6%	0.9 kg
Custom_Special_Function_Board: TMC	0.7 kg	1	0.7 kg	17%	0.8 kg
Power		**19**	**36.4 kg**	**5%**	**38.2 kg**
Thermal Battery (Thermal Battery)	5.0 kg	3	15.1 kg	5%	15.9 kg
Chassis	3.5 kg	1	3.5 kg	5%	3.7 kg
Load Switches (LCC) Boards	1.0 kg	6	6.0 kg	5%	6.3 kg
Thruster Drivers* - MSL GID Boards	1.1 kg	2	2.2 kg	5%	2.3 kg
Pyro Switches* (DPRA) Boards	1.6 kg	4	6.6 kg	5%	6.9 kg
Houskeeping DC-DC Cnvrtrs* (HPCU) Boards	1.1 kg	2	2.3 kg	5%	2.4 kg
Shielding	0.7 kg	1	0.7 kg	5%	0.8 kg

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Descent Stage MEL (continued)

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Propulsion		**91**	**253.1 kg**	**12%**	**283.9 kg**
System 1: Monoprop		91	253.1 kg	12%	283.9 kg
Hardware		91	230.8 kg	13%	261.5 kg
Gas Service Valve	0.2 kg	4	0.9 kg	2%	0.9 kg
HP Transducer	0.3 kg	1	0.3 kg	2%	0.3 kg
Gas Filter	0.8 kg	1	0.8 kg	2%	0.8 kg
NC Pyro Valve	0.7 kg	2	1.3 kg	2%	1.4 kg
NC 3/8" Pyro Valve	0.3 kg	2	0.6 kg	2%	0.6 kg
Press Regulator	1.6 kg	1	1.6 kg	15%	1.8 kg
Temp. Sensor	0.0 kg	2	0.0 kg	5%	0.0 kg
correct to PCA mass 8.94kg	1.7 kg	1	1.7 kg	0%	1.7 kg
Liq. Service Valve	0.3 kg	4	1.1 kg	2%	1.1 kg
Test Service Valve	0.2 kg	1	0.2 kg	2%	0.2 kg
LP Transducer	0.3 kg	4	1.1 kg	2%	1.1 kg
Liq. Filter	0.7 kg	8	5.8 kg	2%	5.9 kg
LP Latch Valve	0.4 kg	2	0.7 kg	2%	0.7 kg
NC Pyro Valve	0.7 kg	8	5.4 kg	10%	5.9 kg
NC 3/8" Pyro Valve	0.3 kg	2	0.6 kg	2%	0.6 kg
Mass Flow Control	0.0 kg	5	0.2 kg	5%	0.2 kg
Temp. Sensor	0.0 kg	10	0.1 kg	0%	0.1 kg
Lines, Fittings, Misc.	5.4 kg	10	54.0 kg	10%	59.4 kg
Monoprop Main Engine	9.1 kg	8	72.8 kg	2%	74.3 kg
Monoprop Thrusters 1	0.7 kg	8	5.9 kg	2%	6.0 kg
Pressurant Tanks	12.5 kg	2	25.1 kg	30%	32.6 kg
Fuel Tanks	12.7 kg	4	50.7 kg	30%	65.8 kg
Pressurant			9.4 kg	0%	9.4 kg
Residuals			13.0 kg	0%	13.0 kg
Mechanical		**8**	**310.0 kg**	**30%**	**403.0 kg**
Struc. & Mech.		7	272.6 kg	30%	354.3 kg
Primary Structure	205.0 kg	1	205.0 kg	30%	266.6 kg
Secondary Structure	4.6 kg	1	4.6 kg	30%	6.0 kg
Separations	10.4 kg	1	10.4 kg	30%	13.5 kg
BUD	32.3 kg	1	32.3 kg	30%	42.0 kg
DS Ballast	5.0 kg	1	5.0 kg	30%	6.5 kg
Purge Hardware	0.8 kg	1	0.8 kg	30%	1.1 kg
Integration Hardware	14.4 kg	1	14.4 kg	30%	18.7 kg
Cabling Harness	37.4 kg	1	37.4 kg	30%	48.6 kg

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Descent Stage MEL (continued)

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Telecom		**25**	**12.9 kg**	**4%**	**13.4 kg**
X-LGA MER/MPF CWG	0.4 kg	1	0.4 kg	2%	0.4 kg
UHF-LGA Monopole	0.6 kg	1	0.6 kg	2%	0.6 kg
SDST X-up/X down	3.0 kg	1	3.0 kg	2%	3.1 kg
X-band TWTA RF=100W	2.5 kg	1	2.5 kg	2%	2.5 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	2	0.9 kg	2%	0.9 kg
X-band Isolator	0.5 kg	1	0.5 kg	0%	0.5 kg
Filter, low power	0.1 kg	2	0.1 kg	2%	0.1 kg
Filter, high power	0.4 kg	2	0.8 kg	0%	0.8 kg
Polarizer	0.3 kg	1	0.3 kg	2%	0.3 kg
Other	0.1 kg	1	0.1 kg	2%	0.1 kg
Coax Transfer Switch (CXS)	0.1 kg	1	0.1 kg	5%	0.1 kg
Other	0.1 kg	1	0.1 kg	2%	0.1 kg
X-band Diplexer, high isolation	0.6 kg	1	0.6 kg	2%	0.6 kg
WR-112 WG, rigid (Al)	0.6 kg	4	2.2 kg	10%	2.4 kg
Coax Cable, flex (190)	0.1 kg	4	0.6 kg	10%	0.6 kg
Coax Cable, flex (120)	0.3 kg	1	0.3 kg	10%	0.3 kg
Thermal		**301**	**23.2 kg**	**26%**	**29.2 kg**
Multilayer Insulation (MLI)	0.4 kg	35	13.1 kg	30%	17.1 kg
Thermal Surfaces		35	0.1 kg	20%	0.1 kg
Paints/Films	0.0 kg	5	0.1 kg	20%	0.1 kg
Thermal Conduction Control		1	0.8 kg	20%	1.0 kg
General	0.8 kg	1	0.8 kg	20%	1.0 kg
Heaters		46	4.6 kg	20%	5.5 kg
Custom	0.1 kg	46	4.6 kg	20%	5.5 kg
Temperature Sensors		140	0.2 kg	5%	0.2 kg
PRT's	0.0 kg	140	0.2 kg	5%	0.2 kg
Thermostats		20	0.3 kg	20%	0.3 kg
Mechanical	0.0 kg	20	0.3 kg	20%	0.3 kg
Other Components		24	4.1 kg	21%	4.9 kg
HRS Tube Assy	2.2 kg	1	2.2 kg	20%	2.7 kg
HRS Epoxy	0.6 kg	1	0.6 kg	10%	0.6 kg
HRS Fluid (CFC-11)	1.1 kg	1	1.1 kg	30%	1.4 kg
Fluid System P-Clamps	0.0 kg	12	0.1 kg	5%	0.1 kg
Fluid System Mech Jt Jam Nuts	0.0 kg	9	0.1 kg	5%	0.1 kg

(End of Descent Stage MEL)

Pallet MEL

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Landed Mass			**783.9 kg**	**27%**	**992.0 kg**
Stack (w/ Wet Element)			**783.9 kg**	**27%**	**992.0 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**783.9 kg**	**27%**	**992.0 kg**
Carried Elements			**554.9 kg**	**20%**	**664.5 kg**
MAX-C Rover			254.9 kg	43%	364.5 kg
EXO Mars Rover			300.0 kg	0%	300.0 kg
Dry Element			**229.0 kg**	**43%**	**327.5 kg**
Wet Element			**229.0 kg**	**43%**	**327.5 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**229.0 kg**	**43%**	**327.5 kg**
System Contingency			**30.1 kg**	**13%**	
Subsystem Heritage Contingency			**68.4 kg**	**30%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**229.0 kg**	**30%**	**297.4 kg**
Attitude Control		**6**	**0.6 kg**	**10%**	**0.7 kg**
Rover Lift Mechanism and Leveling Actuator	0.1 kg	5.0	0.6 kg	10%	0.7 kg
Command & Data		**0**	**0.0 kg**	**0%**	**0.0 kg**
Power		**6**	**7.0 kg**	**30%**	**9.1 kg**
Chassis	0.8 kg	1	0.8 kg	30%	1.0 kg
MSAP Pyro Firing Slice Boards	1.5 kg	4	6.0 kg	30%	7.8 kg
Shielding	0.2 kg	1	0.2 kg	30%	0.3 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**15**	**220.6 kg**	**30%**	**286.8 kg**
Struc. & Mech.		14	209.3 kg	30%	272.1 kg
Primary Structure	54.4 kg	1	54.4 kg	30%	70.7 kg
Secondary Structure	0.1 kg	1	0.1 kg	30%	0.2 kg
Rock Strike Crushable	5.0 kg	1	5.0 kg	30%	6.5 kg
Rover Mounting Structure	8.0 kg	1	8.0 kg	30%	10.4 kg
Lift Separation Hardware	0.6 kg	1	0.6 kg	30%	0.7 kg
Egress Release Hardware	2.2 kg	1	2.2 kg	30%	2.9 kg
Egress Soft Goods	25.0 kg	1	25.0 kg	30%	32.5 kg
Egress Gas Generators	10.0 kg	1	10.0 kg	30%	13.0 kg
Egress Hard Goods	2.0 kg	1	2.0 kg	30%	2.6 kg
Descent Stage Interface Bipods	50.0 kg	1	50.0 kg	30%	65.0 kg
Leveling Actuators	32.0 kg	1	32.0 kg	30%	41.6 kg
Leveling Release Hardware	1.1 kg	1	1.1 kg	30%	1.5 kg
BUD Tower & Bridle Release	15.0 kg	1	15.0 kg	30%	19.5 kg
Integration Hardware	3.8 kg	1	3.8 kg	30%	5.0 kg
Cabling Harness	11.3 kg	1	11.3 kg	30%	14.7 kg

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Pallet MEL (continued)

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Telecom		**0**	**0.0 kg**	**0%**	**0.0 kg**
Thermal		**26**	**0.7 kg**	**6%**	**0.8 kg**
Thermal Surfaces		17	0.4 kg	0%	0.4 kg
General	0.0 kg	17	0.4 kg	0%	0.4 kg
Thermal Conduction Control		1	0.0 kg	0%	0.0 kg
General	0.0 kg	1	0.0 kg	0%	0.0 kg
Heaters		2	0.1 kg	30%	0.1 kg
Custom	0.1 kg	2	0.1 kg	30%	0.1 kg
Temperature Sensors		5	0.1 kg	15%	0.1 kg
Thermistors	0.0 kg	5	0.1 kg	15%	0.1 kg
RHU's	0.1 kg	1	0.1 kg	0%	0.1 kg

(End of Pallet MEL)

MAX-C Rover MEL

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Rover Mass			**254.9 kg**	**43%**	**364.5 kg**
Stack (w/ Wet Element)			**254.9 kg**	**43%**	**364.5 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**254.9 kg**	**43%**	**364.5 kg**
Carried Elements			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**254.9 kg**	**43%**	**364.5 kg**
Wet Element			**254.9 kg**	**43%**	**364.5 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**254.9 kg**	**43%**	**364.5 kg**
System Contingency			**41.9 kg**	**16%**	
Subsystem Heritage Contingency			**67.7 kg**	**27%**	
Payload			**45.2 kg**	**30%**	**58.8 kg**
Instruments		**11**	**45.2 kg**	**30%**	**58.8 kg**
Pancam (Mast, Phoenix, MER)	0.6 kg	2	1.2 kg	30%	1.6 kg
NIR point spectrometer (Mast)	3.5 kg	1	3.5 kg	30%	4.6 kg
Raman Spectrometer (Body)	5.0 kg	1	5.0 kg	30%	6.5 kg
APXS (Mast, MSL)	1.7 kg	1	1.7 kg	30%	2.2 kg
Microscopic imager (Arm) MI design	0.3 kg	1	0.3 kg	30%	0.4 kg
Mast	7.7 kg	1	7.7 kg	30%	10.0 kg
Cache Sample Handling & Container	9.0 kg	1	9.0 kg	30%	11.7 kg
Arm => short, low pre-load	10.3 kg	1	10.3 kg	30%	13.4 kg
Organic Blank	1.5 kg	1	1.5 kg	30%	2.0 kg
Corer/Abrader	5.0 kg	1	5.0 kg	30%	6.5 kg
Additional Payload		**0**	**0.0 kg**	**30%**	**0.0 kg**
Bus			**209.7 kg**	**26%**	**263.9 kg**
Attitude Control		**50**	**7.5 kg**	**22%**	**9.1 kg**
IMU 1	0.8 kg	1.0	0.8 kg	2%	0.8 kg
Distributed Drive Electronics	0.125 kg	42.0	5.3 kg	30%	6.8 kg
Haz Camera	0.3 kg	4.0	1.0 kg	2%	1.1 kg
Nav Camera	0.2 kg	2.0	0.5 kg	2%	0.5 kg
Command & Data		**12**	**12.5 kg**	**7%**	**13.4 kg**
Processor: RAD750	0.6 kg	1	0.55 kg	5%	0.6 kg
Memory: NVMCAM	0.7 kg	1	0.71 kg	30%	0.9 kg
Telecom_I_F: MTIF	0.7 kg	1	0.73 kg	5%	0.8 kg
General_I_F: MSIA	0.7 kg	1	0.71 kg	5%	0.7 kg
Custom_Special_Function_Board: CRC	0.7 kg	1	0.66 kg	5%	0.7 kg
General_I_F: MCIC	0.7 kg	1	0.66 kg	5%	0.7 kg
Power: CEPCU	1.2 kg	2	2.30 kg	5%	2.4 kg
Analog_I_F: MREU	0.8 kg	1	0.82 kg	5%	0.9 kg
Backplane: CPCI backplane (8 slots)	0.8 kg	1	0.84 kg	5%	0.9 kg
Chassis: CDH chassis (8 slot)	3.8 kg	1	3.83 kg	2%	3.9 kg
Custom_Special_Function_Board: MCP TRL6 to Flight	0.7 kg	1	0.71 kg	30%	0.9 kg

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MAX-C Rover MEL (continued)

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Power		**15**	**41.9 kg**	**30%**	**54.5 kg**
GaAs TJ UltraFlex Solar Array (6.02583452714844 m^2)	10.5 kg	1	10.5 kg	30%	13.6 kg
Li-ION (Secondary Battery)	10.0 kg	1	10.0 kg	30%	13.0 kg
Chassis	2.6 kg	1	2.6 kg	30%	3.3 kg
MSAP Array Interface Slice Boards	2.0 kg	1	2.0 kg	30%	2.6 kg
MSAP Power Switch Slice Boards	1.6 kg	4	6.5 kg	30%	8.5 kg
MSAP Pyro Firing Slice Boards	1.5 kg	2	3.0 kg	30%	3.9 kg
MREU (Mass in Power, Cost in C&DH) Boards	1.0 kg	1	1.0 kg	30%	1.3 kg
MSAP Power Converter Unit Boards	1.0 kg	1	1.0 kg	30%	1.3 kg
SMAP Power Bus Control Slice Boards	4.0 kg	1	4.0 kg	30%	5.2 kg
MSL Battery Control Board Boards	0.8 kg	1	0.8 kg	30%	1.0 kg
Shielding	0.6 kg	1	0.6 kg	30%	0.7 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**9**	**115.7 kg**	**30%**	**150.5 kg**
Struc. & Mech.		8	94.5 kg	30%	122.8 kg
Primary Structure	32.3 kg	1	32.3 kg	30%	42.0 kg
Secondary Structure	3.4 kg	1	3.4 kg	30%	4.4 kg
Solar Array Latch/Release	0.6 kg	1	0.6 kg	30%	0.8 kg
Antenna Gimbal Assemblies	3.9 kg	1	3.9 kg	30%	5.1 kg
Mobility Drive Actuators	9.6 kg	1	9.6 kg	30%	12.5 kg
Mobility Steer Actuators	6.4 kg	1	6.4 kg	30%	8.3 kg
Mobility Structure	36.0 kg	1	36.0 kg	30%	46.8 kg
Integration Hardware	2.3 kg	1	2.3 kg	30%	2.9 kg
Cabling Harness	21.3 kg	1	21.3 kg	30%	27.7 kg
Telecom		**29**	**15.1 kg**	**7%**	**16.2 kg**
X-HGA (22dB) MPF	1.6 kg	1	1.6 kg	2%	1.6 kg
X-LGA MER/MPF CWG	0.4 kg	1	0.4 kg	2%	0.4 kg
UHF-LGA Quadrafilar Helix (Reconfigurable)	0.6 kg	1	0.6 kg	2%	0.6 kg
SDST X-up/X down	3.0 kg	1	3.0 kg	2%	3.1 kg
Electra-Lite	2.9 kg	1	2.9 kg	2%	2.9 kg
X-band SSPA, RF=15W*	1.4 kg	1	1.4 kg	2%	1.4 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	2	0.9 kg	2%	0.9 kg
X-band Diplexer, high isolation	0.6 kg	1	0.6 kg	2%	0.6 kg
Filter, low power	0.1 kg	1	0.1 kg	2%	0.1 kg
Filter, low power	0.1 kg	1	0.1 kg	2%	0.1 kg
Coax Transfer Switch (CXS)	0.1 kg	1	0.1 kg	2%	0.1 kg
Other	0.1 kg	1	0.1 kg	2%	0.1 kg
Other	0.1 kg	1	0.1 kg	10%	0.1 kg
WR-112 WG, rigid (Al)	0.6 kg	4	2.2 kg	25%	2.8 kg
Coax Cable, flex (190)	0.1 kg	8	0.8 kg	25%	1.0 kg
Coax Cable, flex (120)	0.1 kg	3	0.3 kg	25%	0.4 kg

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MAX-C Rover MEL (continued)

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Thermal		**188**	**16.9 kg**	**19%**	**20.2 kg**
Heaters		24	1.2 kg	30%	1.6 kg
Custom	0.1 kg	24	1.2 kg	30%	1.6 kg
Temperature Sensors		100	1.0 kg	15%	1.2 kg
PRT's	0.0 kg	100	1.0 kg	15%	1.2 kg
Thermostats		24	0.5 kg	15%	0.6 kg
Mechanical	0.0 kg	24	0.5 kg	15%	0.6 kg
RHU's	0.1 kg	22	2.2 kg	15%	2.5 kg
Other Components		9	12.0 kg	20%	14.4 kg
Shunt Heater Stirps	2.5 kg	1	2.5 kg	30%	3.3 kg
Heaters and EMI Protection	1.3 kg	1	1.3 kg	30%	1.7 kg
Battery Thermal Control Assembly	1.0 kg	1	1.0 kg	30%	1.3 kg
Thermal Collection Plate HRS Rover	0.6 kg	1	0.6 kg	30%	0.8 kg
Cruise Loop/Fluid/Flex Bellows	2.8 kg	1	2.8 kg	20%	3.4 kg
InterConnect tubes	3.1 kg	1	3.1 kg	5%	3.2 kg
HRS Tubing Epoxy+Bulkhd Nut	0.7 kg	1	0.7 kg	5%	0.8 kg

(End of MAX-C Rover MEL)

MAX-C Rover MEL (continued)

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Thermal		**188**	**16.9 kg**	**19%**	**20.2 kg**
Heaters		24	1.2 kg	30%	1.6 kg
Custom	0.1 kg	24	1.2 kg	30%	1.6 kg
Temperature Sensors		100	1.0 kg	15%	1.2 kg
PRT's	0.0 kg	100	1.0 kg	15%	1.2 kg
Thermostats		24	0.5 kg	15%	0.6 kg
Mechanical	0.0 kg	24	0.5 kg	15%	0.6 kg
RHU's	0.1 kg	22	2.2 kg	15%	2.5 kg
Other Components		9	12.0 kg	20%	14.4 kg
Shunt Heater Stirps	2.5 kg	1	2.5 kg	30%	3.3 kg
Heaters and EMI Protection	1.3 kg	1	1.3 kg	30%	1.7 kg
Battery Thermal Control Assembly	1.0 kg	1	1.0 kg	30%	1.3 kg
Thermal Collection Plate HRS Rover	0.6 kg	1	0.6 kg	30%	0.8 kg
Cruise Loop/Fluid/Flex Bellows	2.8 kg	1	2.8 kg	20%	3.4 kg
InterConnect tubes	3.1 kg	1	3.1 kg	5%	3.2 kg
HRS Tubing Epoxy+Bulkhd Nut	0.7 kg	1	0.7 kg	5%	0.8 kg

(End of MAX-C Rover MEL)